Water Research 262 (2024) 122098

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Global perspectives on groundwater infiltration to sewer networks: A threat to urban sustainability

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ARTICLE INFO

Keywords:
Groundwater
Infiltration
Modelling
Urban groundwater
Sewer networks

ABSTRACT

While existing studies on sewer networks have explored topics such as surface water inflow, limited research has delved into groundwater infiltration (GWI). This study aims to fill this void by providing a comprehensive overview of quantitative analyses of GWI in sewer networks plus current status, limitations and future perspectives, considering the most relevant peer-reviewed research, including 83 studies. We propose dividing the existing research into two main groups: (1) phreatic zone, and (2) vadose zone. Most research has focused on the latter, mainly considering Rainfall-Derived Inflow and Infiltration (RDII), including surface water inflow and GWI. The ratio of each is not frequently separated; otherwise, there may be some assumptions, e.g. in dry weather and assuming zero surface water inflow. We also divided the employed approaches in different categories from physically-based numerical models, to simpler ones, e.g. water budget analysis. In fact, a combination of approaches may be applied to find the intricate characteristics of 'urban groundwater' or 'urban karst.' The findings revealed a heightened vulnerability of sewer networks to GWI, due to climate change (CC) and its associated repercussions, e.g. sea level rise (SLR), making the coastal cities the most vulnerable regions. In future research, the criticality of pre-emptive measures and monitoring of networks, especially near the coastline, is emphasised to ensure the resilience and adaptability of sewer networks in the context of GWI amid the potential impacts of CC. However, current monitoring practices lack widespread evidence for spatiotemporal analysis of GWI quantity.

1. Introduction

As indispensable and worldwide natural reservoirs, groundwater systems play a central role in the context of human civilisation, hygiene, and the conservation of ecosystems and all forms of life (Barik et al., 2017). However, aquifers are currently facing various pressures (Zeydalinejad, 2023; Zeydalinejad and Nassery, 2023), including land cover/ land use (LC/LU) changes, excessive pumping, groundwater pollution, population growth, increased agriculture, industrial expansion, and climate change (CC), making them significant global concerns (Anbarasu et al., 2020; Halder et al., 2020). Currently, the growing challenges of CC, urbanisation, and shifts in the hydrological cycle pose escalating threats from groundwater, including groundwater infiltration (GWI) in sewer networks, which can damage or constrain network capacity and undermine to the ability of sewer networks to safely transport flow (Jato-Espino et al., 2019).

Groundwater can have adverse effects on various facets of human existence, such as GWI causing detrimental impacts on infrastructure, including wastewater or sewer networks, due to elevated groundwater level (GWL) (Abd-Elaty et al., 2022). Coastal cities with aging sewer infrastructures in areas characterised by shallow aquifers are particularly susceptible to these challenges (Liu et al., 2021). Anticipated increases in sea levels will elevate coastal water tables, giving rise to groundwater risks that imperil shallow infrastructure and the resilience of coastal ecosystems (Befus et al., 2020).

Wastewater collection networks constitute a crucial component of contemporary society's critical infrastructure (Ghavami et al., 2020). However, the occurrence of GWI leads to substantial adverse

Abbreviations: AI, artificial intelligence; CC, climate change; CSOs, combined sewer overflows; DWCs, dry weather conditions; GIS, geographic information system; GWF, groundwater flow; GWI, groundwater infiltration; GWL, groundwater level; I/I, inflow and infiltration; LC/LU, land cover/ land use; NBS, nature-based strategies; RDII, rainfall-derived inflow and infiltration; SLR, sea level rise; SWMM, storm water management model; WWCs, wet weather conditions.

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https://doi.org/10.1016/j.watres.2024.122098
Received 1 May 2024; Received in revised form 28 June 2024; Accepted 13 July 2024
Available online 19 July 2024
0043-1354/

consequences, including uncontrolled discharge of untreated sewage, diminished system capacity, structural deterioration, and dilution of wastewater reaching treatment plants, causing operational disruptions (Liu et al., 2021).

The malfunction of urban sewer networks introduces a spectrum of risks to environmental safety, encompassing air, water, and soil (Iurchenko et al., 2016; Rutsch et al., 2005). Among the key components of wastewater collection networks, combined sewer networks (Laakso et al., 2018), serve as conduits for transporting waste and stormwater (a combination of foul and storm sewage) from residential, commercial, and industrial areas to wastewater treatment facilities (Ghavami et al., 2020).

GWI leads to approximately 16 % of the typical defects found in sewer networks and is identified as a significant factor contributing to their suboptimal condition (Moselhi and Shehab-Eldeen, 1999a; Shehab-Eldeen, 2001). In some studies, it has been indicated that infiltration may be responsible for up to 40 % of the overall flow in sewer networks (Aguiar et al., 1996). In German sewer networks, for instance, wastewater flow includes up to 40 % of groundwater (Wittenberg and Brombach, 2002).

Studies consistently identify that mitigating the risk of GWI to sewer networks is of significant importance (Chughtai and Zayed, 2008). However, the existing literature on GWI in sewer networks is limited, primarily consisting of case studies. This gap in research is noteworthy and should be addressed to support sustainability of infrastructure's effectiveness at safeguarding human and environmental health. Even though different reviews on various aspects of sewer networks have been conducted, especially during the recent years (Table 1), a comprehensive review study that considers various factors related to the quantification of GWI in sewer networks is lacking, especially regarding the phreatic zone of the aquifer.

The primary aim of the current study is to offer a comprehensive overview of existing studies on GWI in sewer networks, including their subjects, modelling approaches, studied areas, data, scales, challenges, and key findings. Through this approach, the study aims to furnish detailed insights into the current state of knowledge, and to pave the way for discussions on future directions. The study outlines future adaptive strategies aimed at urban sustainability and resilience. It is important to note that the study primarily focuses on the quantification of GWI in sewer networks, rather than delving into groundwater quality considerations undertaken by Jia et al. (2021) and Sridhar and Parimalarenganayaki (2024). Finally, this study does not focus on discussions regarding the characteristics of sewer networks, e.g. their deterioration, as addressed by Salihu et al. (2022).

Table 1
Different review articles related to sewer networks.

Topic	Reference
Sewer leakage	Rutsch et al. (2006)
Methods for calculating sewage exfiltration to urban groundwater	Chisala and Lerner (2008)
Wastewater management through the ages	Lofrano and Brown (2010)
Captured streams and springs in sewer networks	Broadhead et al. (2013)
The historical development of sewer networks	De Feo et al. (2014)
Impacts and managerial implications for sewer networks regarding changes to inputs in domestic wastewater	Mattsson et al. (2015)
Impact of underground structures on the flow of urban groundwater	Attard et al. (2016a)
Stormwater infiltration and urban karst	Bonneau et al. (2017)
Mitigation of basement flooding due to sewer backup	Irwin et al. (2018)
Approaches to modelling sewer solids	Murali et al. (2019).
Sewer asset management	Tscheikner-Gratl et al. (2019)
Condition of sewer pipes	Malek Mohammadi et al. (2020)
Neurocomputing in surface water (including sewer networks) hydrology and hydraulics	Zounemat-Kermani et al. (2020a)
Water quality modelling in sewer networks	Jia et al. (2021)
Adaptation of urban drainage networks to CC	Kourtis and Tsihrintzis (2021)
Sewer exfiltration to groundwater in urban wastewater systems	Nguyen et al. (2021)
I/I to wastewater sewer networks	Ohlin Saletti (2021)
Sewer networks in China	Wang et al. (2021)
Sewer overflow impacts on the environment	Owolabi et al. (2022)
Sewer leakage detection	Sadeghikhah et al. (2022)
Deterioration factors and modelling of sewer pipelines	Salihu et al. (2022)
Sewer overflow impacts on public health	Sojobi and Zayed (2022)
Variability in wastewater quality and in-sewer processes during conveyance in sewer networks	Gao et al. (2023)
The influence of SLR on groundwater and municipal infrastructure	Habel et al. (2023)
CC impacts on sewer infrastructure	Li et al. (2023a)
Groundwater contamination due to sewer leakage	Sridhar and Parimalarenganayaki (2024)

2. Theoretical background

2.1. Sewer networks are crucial urban infrastructure

With over half of the global population residing in urban areas and ongoing worldwide urbanisation (United Nations, 2019), a growing focus on urban water resources exists (Birks et al., 2013; Ehleringer et al., 2016; Farr et al., 2017; Lundy and Wade, 2011; McGrane, 2016; Mitchell, 2006).

Urbanisation has seen an increased utilisation of the underground environment, leading to a substantial connection between groundwater and subterranean infrastructure (Sartirana et al., 2022). This connection can lead to water infiltrations, corrosion, and stability concerns for underground structures (Sartirana et al., 2022), compounded by factors such as cracks, leaks, defective pipe joints, broken pipes, sewer age, defect sizes, and pipe materials (Su et al., 2020; Thapa et al., 2019).

Sewer networks usually consist of buried infrastructure, including pipes, manholes, pumping stations, overflow structures, and other hydraulic facilities (Joseph-Duran et al., 2015), constituting substantial investments in infrastructure (Jia et al., 2021). Modern sewer networks consist of three primary types: (1) sanitary sewers, alternatively known as foul sewers, (2) storm sewers, also referred to as surface water sewers, and (3) combined sewers (De Feo et al., 2014).

Traditionally, sewer networks have been engineered to gather wastewater and stormwater, transporting them to wastewater treatment plants for processing or disposal (Jia et al., 2021; Martin and Vanrolleghem, 2014; Haghighi and Bakhshipour, 2015). These sewer networks are commonly known as combined sewer networks since they convey a mixture of wastewater and stormwater (Hager and Gisonni, 2005). Nevertheless, numerous cities have opted to separate combined sewer networks into distinct storm sewers (storm drainage systems or infiltration facilities) and foul sewer systems (Thorndahl et al., 2015; Mahaut and Andrieu, 2019). In this separation, storm sewers convey urban runoff to surface waters, while foul sewer systems transport sewage collected from residential and commercial buildings to treatment facilities. This segregation proves advantageous for urban water environments as it helps prevent combined sewer overflows (CSOs) (Joseph-Duran et al., 2015; Mollerup et al., 2015). However, in many cities with separated systems, unauthorized connections between storm drainage and sewer networks are frequently observed, leading to the pollution of stormwater with sewage or the hydraulic overload of foul sewers due to inflow and infiltration (I/I) (Panasiuk et al., 2016).

Urban water infrastructure includes distribution and treatment, e.g. water supply and sewer networks (Mair et al., 2017). Detecting and quantifying extraneous inflows and infiltration, with a specific focus on GWI, have consistently been recognised as significant challenges in urban sewer networks (Zhu, 2022). Identifying and measuring GWI represent the initial and essential stages in achieving sewer rehabilitation and management that are more efficient, cost-effective, and sustainable (Zhu, 2022).

2.2. Groundwater interacts with sewer networks

Wastewater is recognised as a prominent source of various pollutants, including nutrients, bacteria, and organic contaminants (Clemens et al., 2020). Insufficient sanitation practices and the uncontrolled discharge of untreated wastewater into the environment result in contamination of surface water, soil, and groundwater (Foster et al., 2013).

Wastewater compounds are commonly identified in urban shallow groundwater, with potential sources including sewage or treated wastewater (Lee et al., 2015). In recent times, the problem of elevated GWL has garnered significant concern (Becker et al., 2022). High GWL can have adverse effects, particularly causing harm to structures, infrastructure, and the surrounding environment (Becker et al., 2022). These elevated GWL can be the result of various factors, including hydrological influences such as intense or prolonged rainfall and flooding, as well as human activities like decreased groundwater extraction, interactions with sewer networks, hydraulic engineering practices, alterations to the water balance, and mining operations (Becker et al., 2022).

Groundwater can enter the sewer networks via pipe imperfections (Zhang and Parolari, 2022). In fact, groundwater, or infiltration in this context, finds its way into combined and sanitary sewer networks through defects located in saturated soil (Staufer et al., 2012). Moreover, increased hydraulic loads have the potential to impose additional annual expenses on both the collection systems and treatment facilities, such that pressurised connections resulting from these hydraulic loads may pose a risk of raw sewage pollution to the community and the environment (Sangsefidi et al., 2023b).

The most prevalent terms for non-authentic wastewater in sewer networks are "Infiltration" and "Inflow" (I/I). Occasionally, the term "parasite water" is also utilised, emphasising the concept that sewer capacity and wastewater treatment plants are designed for genuine wastewater, and the presence of I/I is considered undesirable (Hey et al., 2016). GWI has been defined by Sowby and Jones (2022) referring to water entering a sewer system from the ground through faulty pipes, pipe joints, connections, or manholes, not necessarily due to current wet periods. GWI can be quantified on dry weather conditions (DWCs); however, the RDII is usually analysed on wet weather conditions (WWCs) and usually for each rain event (Ye et al., 2023). DWCs were characterised as consecutive days without precipitation, while WWCs were identified as a 24-hour rainfall event with a 25-year return period (Sangsefidi et al., 2023b). In some cases, because of specific climate conditions, e.g. lack of surface water inflow, GWI into the sewer networks may account for the entirety of I/I (Heiderscheidt et al., 2022).

The risk of GWI in sewer networks depends on a myriad of factors, among which geological formations, including alluvial and hard-rock (karst) ones. We propose a schematic of GWI in sewer networks in these two aquifers, as follows:

- Alluvial aquifers (Fig. 1): GWI can occur physically when the pipe is located entirely or partially below the water table, both spatially and temporally (DeSilva et al., 2005; Dirckx et al., 2016). Otherwise, either sewerage exfiltration to aquifer or RDII to sewer networks may be expected. Another probability is fluctuations of wastewater level in sewer networks when GWL is near them with the potential of either GWI or wastewater exfiltration. Exfiltration rates are highly sensitive to in-sewer water levels (Karpf et al., 2011).
- Hard-rock (karst) aquifers (Fig. 2): There are three types of groundwater flow (GWF) in these groundwater systems (Ford and Williams, 2007): (1) conduit GWF in caves and big fractures, for

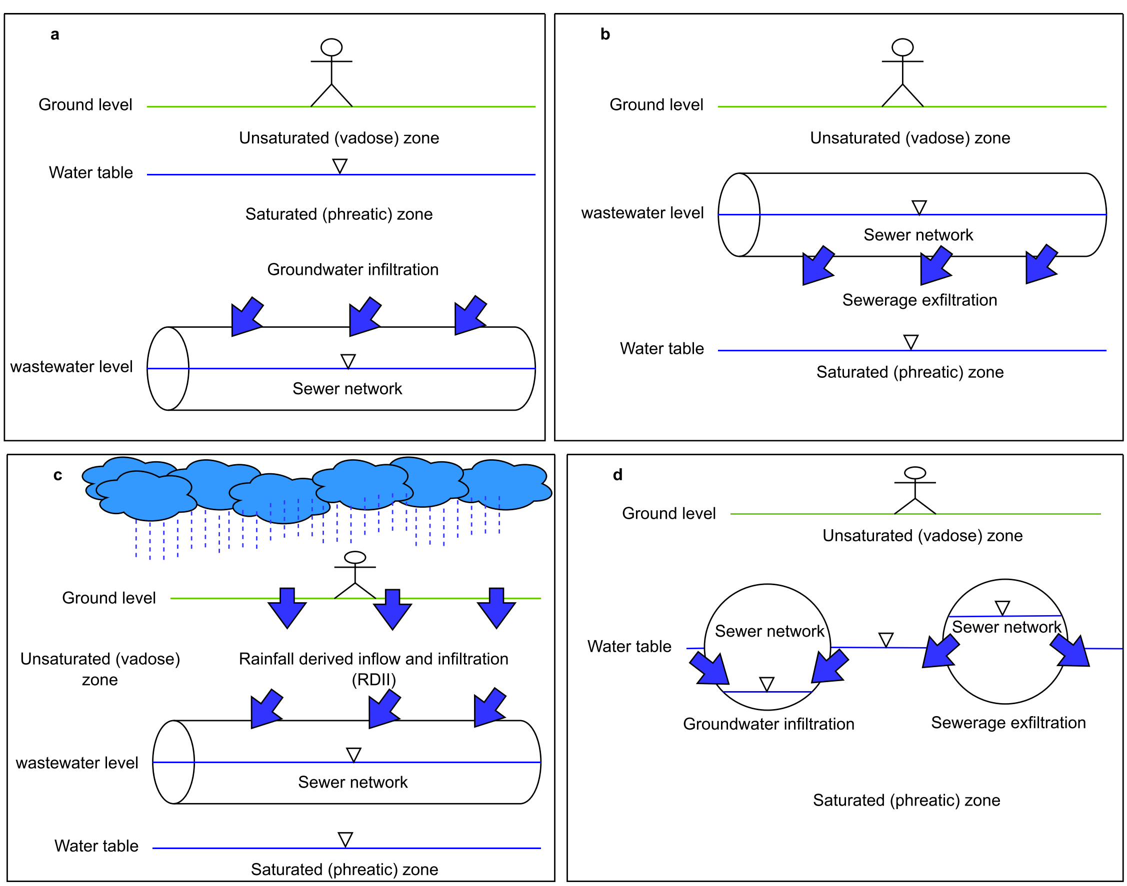

Fig. 1. GWL above sewer networks, inducing GWI in them (a), GWL below sewer networks, making sewerage exfiltration in aquifer (b), GWL below sewer networks and RDII in them (c), and fluctuations in wastewater level, whether GWI in sewer networks or sewerage exfiltration in aquifer (d).

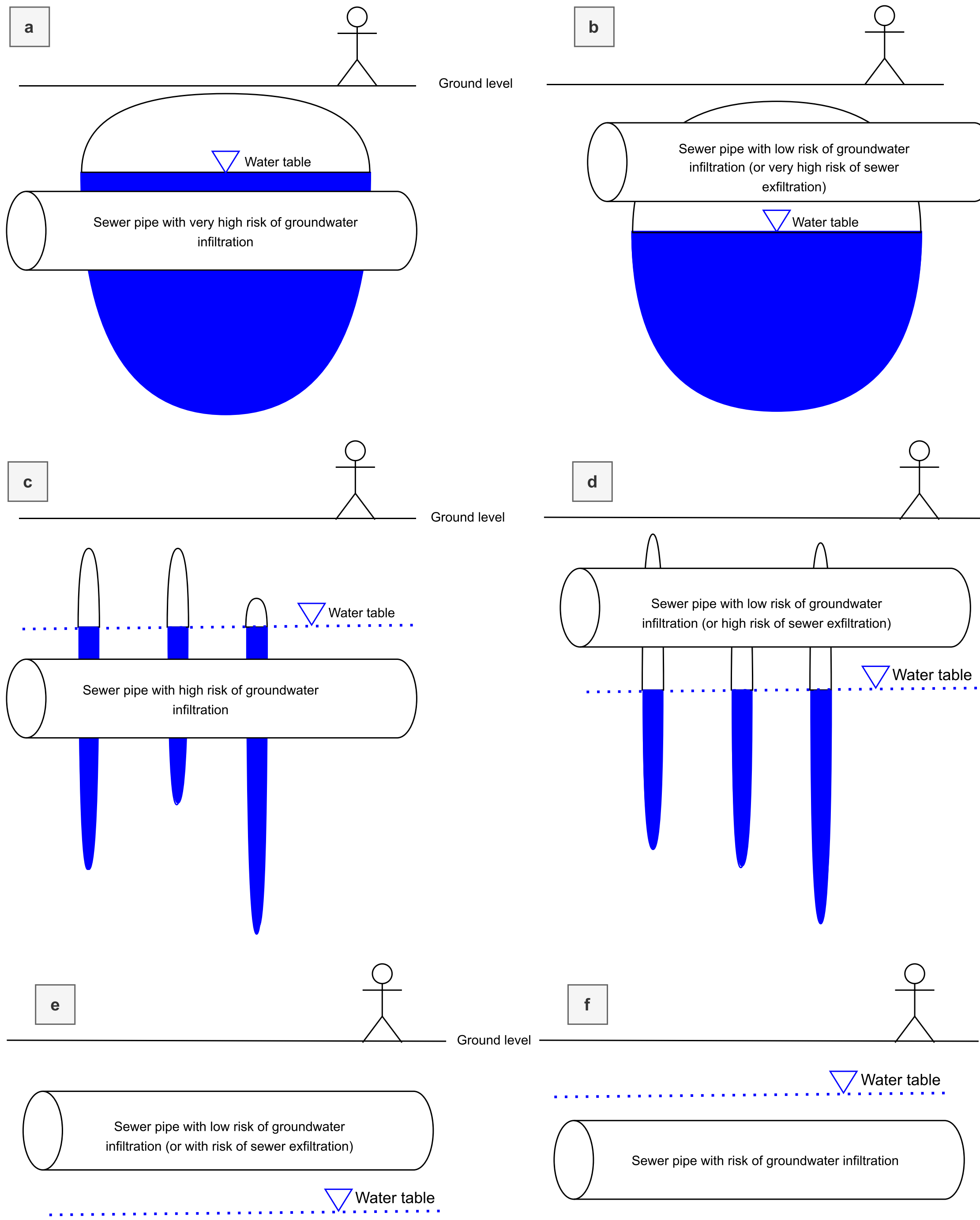

Fig. 2. Different GWF patterns in Hard-rock aquifers and sewer networks, including: (a) GWF in caves and huge fractures with GWL above sewer networks (very high risk), (b) GWF in caves and huge fractures with GWL below sewer networks (very high potential risk), (c) GWF in conduits with GWL above sewer networks (high risk), (d) GWF in conduits with GWL below sewer networks (high potential risk), (e) diffuse GWF in rock's matrix with GWL below sewer networks (low risk), and (f) diffuse GWF in rock's matrix with GWL above sewer networks (potential risk).

which the risk of GWI in sewer networks (GWL above sewer networks) or the risk of sewer exfiltration to groundwater (GWL below sewer networks) may be very high. (2) Conduit GWF in conduits (smaller fractures), for which the risk of GWI in sewer networks (GWL above sewer networks) or the risk of sewer exfiltration to groundwater (GWL below sewer networks) may be high. (3) diffuse GWF in rock's matrix, for which the risk of GWI in sewer networks may be low (GWL above sewer networks) or potentially low (GWL below sewer networks).

2.3. *Surface water plays a significant role in both groundwater dynamics and GWI in sewer networks*

Groundwater, as an integral component of the water cycle, exhibits dynamic interconnections with surface water bodies like rivers, streams, lakes, and wetlands (Ntona et al., 2022; Winter, 1995). Indeed, the global interaction between surface water and groundwater involves processes such as surface water recharging groundwater and groundwater exfiltrating onto the soil surface or discharging through stream beds as return flow (Sechu et al., 2022). This interconnection may be contingent on the hydrogeological regime and climatic conditions

(Ntona et al., 2022). For example, in certain situations, rivers recharge groundwater during the wet season, whereas during dry periods, groundwater contributes to sustaining river baseflow (Mukherjee et al., 2018; Ntona et al., 2022). These interactions can impact the quality and conditions of both water bodies, influencing the ecosystems they support (Sechu et al., 2022).

In urban flood modelling, the significance of the impact of sewer networks on overland flow is well-established (Chen et al., 2016; Martínez et al., 2021; Bazin et al., 2014). Equally important is the consideration of the interaction between surface water and infiltration losses to enhance the estimation of inundation extent and water depths (Mallari et al., 2015; Martínez et al., 2019, 2021; Park et al., 2019). Based on hourly measurements of rainfall and flowrates, Belhadj et al. (1995) devised a conceptual model to replicate rainfall-induced infiltration into sewer networks in France. Sensitivity analysis conducted on the model demonstrated favourable outcomes across different calibration scenarios, yet it also highlighted significant parameter interactions that could pose a challenge for certain specific model applications.

2.4. Climate change (CC) is altering the hydrologic cycle components, including groundwater dynamics

CC involves both natural and anthropogenic influences affecting terrestrial climate and the hydrologic cycle (Green et al., 2011). In fact, CC has the potential to affect the quantity and quality of various components within the global hydrologic cycle across spatial, temporal, and frequency domains (Loaiciga et al., 1996; Sharif and Singh, 1999; Milly et al., 2005; Holman, 2006). Elements of the surface hydrologic cycle that may face impacts from CC include atmospheric water vapor content, precipitation and evapotranspiration patterns, snow cover, melting of ice and glaciers, soil temperature, soil water content, and surface runoff and stream flow (Bates et al., 2008).

The consensus among the majority is that CC has led to, and will continue to bring about, more severe and frequently extreme weather events (Zhang et al., 2018a). The Nordic countries, for instance, are anticipated to experience elevated levels of precipitation because of CC (Jenssen Sola et al., 2018).

Expected shifts in global climate are poised to impact the hydrological cycle, resulting in modifications to surface-water levels and groundwater recharge to aquifers, thereby influencing natural ecosystems and human activities in various ways (Green et al., 2011).

Changes to the atmospheric and surface components of the global hydrologic cycle are expected to bring about alterations in the subsurface hydrologic cycle within the soil, vadose zone, and aquifers globally (Van Dijck et al., 2006). Earlier snowmelt leads to heightened soil water content during a period of relatively low potential evapotranspiration (Barnett et al., 2008), potentially increasing infiltration and recharge in mountainous regions (Green et al., 2011). CC and climate variability are expected to have diverse effects on recharge rates and mechanisms (Vaccaro, 1992; Green et al., 2007; Kundzewicz et al., 2007; Aguilera and Murillo, 2009). While many CC studies have predicted reduced recharge (Herrera-Pantoja and Hiscock, 2008), it is important to note that the impact of CC on recharge may not uniformly be negative for all aquifers or throughout all periods (Jyrkama and Sykes, 2007; Döll, 2009; Gurdak and Roe, 2010). In truth, groundwater systems are expected to demonstrate dissimilar response to CC, such that coastal aquifers face susceptibility to rising sea levels (Döll, 2009) and saltwater intrusion (Green et al., 2011).

2.5. Negative impacts can arise from sewer systems interactions with groundwater

Sewer networks affect groundwater resources in various ways. One such impact is the contribution to the absence of streams and springs, as demonstrated by a specific case study in the UK, where 50 % of the entire stream length and over 100 natural springs had possibly disappeared and could be discharging into the combined sewer networks (Broadhead et al., 2015). Additionally, sand erosion near damaged sewer pipes, influenced by groundwater, presents another issue, as asserted by Guo et al. (2013). Even though sewerage exfiltration deteriorates groundwater quality, establishing sewer networks can also improve groundwater quality significantly, like the study conducted in the Great Hungarian Plain using GIS and multivariate statistical analysis (Mester et al., 2021).

Consideration must be given to the attributes of sewer networks, such as their aging, which can impair the system's functionality and result in adverse consequences for the urban environment, such that older pipes may become damaged and create opportunities for water ingress or egress, potentially causing the leakage of untreated sewage or permitting GWI. In the latter scenario, this additional water could lead to increased instances of CSOs events (Su et al., 2020).

In numerous countries, including northern regions, sewage networks have reached an age requiring renovation (Heiderscheidt et al., 2022). Unauthorised connections or misconnections in residential areas may be another challenge which may constitute a major avenue for stormwater entering the sewer networks (Tan et al., 2019). Considerable emphasis has been placed on the necessity of restoring and upgrading aging sewer networks. However, the age factor does not exclusively account for sewer failures. Significant performance issues have arisen in sewerage projects with less than a decade of operation (Fenner, 1990).

The deterioration of sewer networks, such as the development of cracks along their walls and misaligned joints, promotes the escape of wastewater (exfiltration) and the entry of groundwater (infiltration) (Beheshti and Sægrov, 2018; Bradbury et al., 2013; De Bénédittis and Bertrand-Krajewski, 2005a; Howard and Gerber, 2018; Karpf and Krebs, 2011; Kracht et al., 2007; Su et al., 2020; Wittenberg and Aksoy, 2010; Wolf et al., 2004). Wastewater has been identified as a significant source of groundwater contamination, having the capacity to infiltrate into groundwater reservoirs (Burri et al., 2019). Sewer networks harbour a blend of harmful gases produced through the biodegradation of waste and sewage within the conduits, constituting a potentially dangerous gas composition that poses a significant risk to neighbouring communities (Ojha et al., 2017). The seepage of untreated wastewater into groundwater systems poses a significant threat to the accessibility of freshwater for human use and environment (Brokamp et al., 2017; Clemens et al., 2020; Donovan et al., 2008; McGinnis et al., 2018; Sercu et al., 2011; Su et al., 2020). The escalating issue of a shortage of safe drinking water demands immediate measures to safeguard groundwater resources (Clemens et al., 2020).

Dealing with the existing issues in modelling GWI into sewer networks through rehabilitation efforts is crucial but often comes with substantial costs (Zounemat-Kermani et al., 2020a). GWI in sewer networks leads to additional sewer water, resulting in increased water bill of the citizens (Guo, 2017). Conducting regular inspections of sewer networks is not economically viable, given the constraints of time, the expense associated with assessment technologies, and the extensive inventory of pipes (Malek Mohammadi et al., 2019).

Various countries employ distinct solutions, influenced in part by diverse climatic and environmental conditions, as well as variations in legislation and perspectives regarding overflow issues, economic considerations, and the feasibility of available solutions. Although some countries have I/I control manuals, e.g. Australia, US, and New Zealand, some developed countries like Denmark and Sweden do not have national guidelines. Plus, in Germany and the Netherlands a large part of the sewer networks is still combined although separate systems are politically preferred (Hey et al., 2016).

3. Research methodology

This study employed a systematic methodology, including all peer reviewed articles available on Google Scholar and Web of Science featuring relevant keywords from 2001 to 2024. Keywords used included, but not limited to, "sewer systems", "wastewater systems", "sewer networks", "groundwater systems", "aquifers", and "infiltration". We combined search strings from these keywords to create comprehensive search queries, such as: (1) "sewer systems" AND "groundwater infiltration", (2) "sewer networks" AND "aquifer", (3) "sewerage" AND "groundwater level", (4) "sewer" AND "groundwater modelling".

The inclusion criteria for selecting studies were: (1) peer-reviewed status, (2) publication in English, and (3) relevance to GWI in sewer networks. To determine relevance, we first scrutinised the abstract of each study. If the abstract matched our topic, we scanned the entire context. If it continued to align with our focus, we then thoroughly reviewed the entire research study before making a final selection.

Altogether, 83 research papers were screened for relevance, comprising 45 studies on GWI into sewer networks in the phreatic zone and 38 studies in the vadose zone. Most of the selected research studies are peer-reviewed journal papers (Fig. 3).

It is acknowledged that there is the potential for records from other databases to be missed from this search methodology. However, applying Google Scholar, the largest academic database, as the basis for this literature search, along with Web of Science ensures that it is likely that the results will sufficiently represent the primary advancements and essential characteristics of GWI in sewer networks. The insights were intended to build a comprehensive understanding of current knowledge regarding vulnerabilities in groundwater and sewer systems, represented through various schematic frameworks. This methodological approach ensures the incorporation of diverse perspectives and findings, enhancing the robustness and credibility of the research outcomes.

4. Systematic review

Several studies have focused on the impact of sewer networks, e.g. sewerage exfiltration, on groundwater quantity from laboratory to national scales (Table 2). Rutsch et al. (2008), Nguyen et al. (2021) and Chisala and Lerner (2008) provide critical reviews of the impacts of sewer networks on groundwater; the latter also reviewing the methods used for calculating sewage exfiltration to urban groundwater. Some research studies have focused on the impacts of wastewater systems on

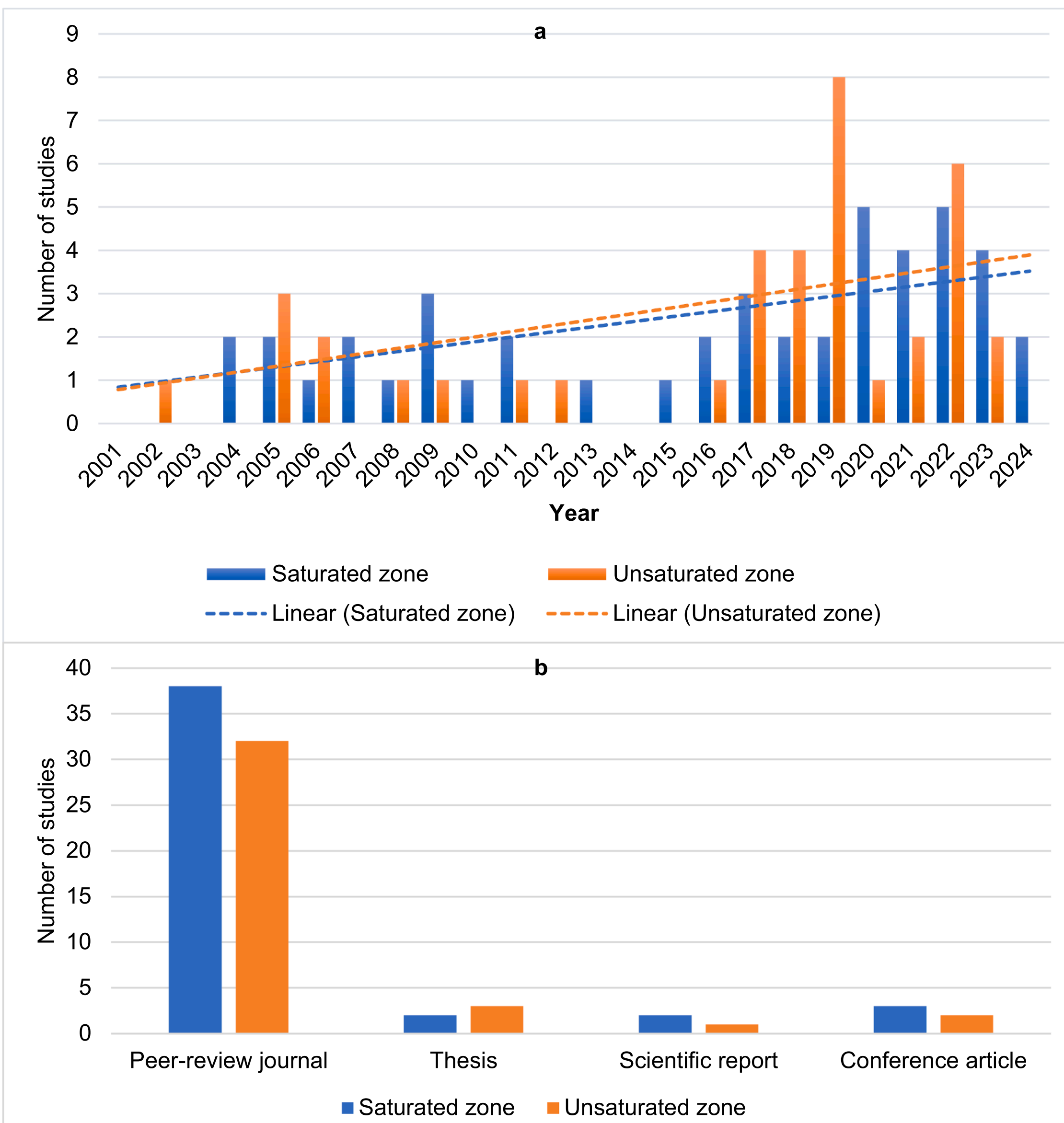

Fig. 3. Visual representation of the trajectory of case studies investigating GWI in sewer networks spanning from 2001 to 2024, encompassing studies conducted on both the phreatic (saturated) and vadose (unsaturated) zones of the aquifer (a) and the number of different types of selected studies (b).

Table 2
Example studies concentrating on sewer exfiltration in groundwater.

Subject	Study area	Approach	Conclusion	Reference
Leaking sewer networks influence on urban groundwater	Plittersdorf, Germany	Groundwater sampling	Damaged sewer networks are the primary source of groundwater contamination in the region, depending on the geology and mineralogy of the sewer's surrounding.	Eiswirth and Hötzl (1997)
Wastewater impact on groundwater	Laboratory	Water and Transport Model (WTM)	Analyses of the pore size distribution in soil columns exposed to long-term wastewater infiltration indicate clogging effects due to chemical or microbial transformation processes.	Mohrlok et al. (2004)
Exfiltration in sanitary sewer networks	USA	Analysis of wastewater flow surface and GWL data	Combination of low GWL and shallow sewer networks provides the potential for extensive exfiltration, as in the western USA.	Selvakumar et al. (2004)
Incorporating sewer networks into numerical groundwater models	Rastatt, Germany	FEFLOW; Hydrochemical analysis; water sampling; GIS	The measurable impact of a solitary sewer leak, featuring an exfiltration rate of 1 m^3/day, is rather restricted within a 20 m thick aquifer with hydraulic conductivities of 1*10–3 m/s. The associated increase in the GWL is less than 1 cm within a 10 m radius from the leak.	Wolf (2004)
Quantify sewer leakage to groundwater	Linz, Austria	Carbamazepine as a tracer	Results show an average exfiltration rate of 1 %, expressed as percentage of the dry weather flow that is lost to the groundwater.	Fenz et al. (2005)
Computing sewer exfiltration	Rümlang, Switzerland	Artificial tracers	Exfiltration rate is quantified to be 9.9 %.	Rieckermann et al. (2005, 2007)
Distribution of sewer exfiltration to urban groundwater	Nottingham, UK	GIS	Considering the current replacement/renewal frequency of once every 1300 years, sewer networks of all ages pose a potential risk to urban groundwater.	Chisala and Lerner (2008)
Groundwater recharge estimation, considering sewerage leakage as a recharge source	Deklab County, USA	GIS and MODFLOW	The study predicts that urbanisation results in 7–10 ft decrease in GWL of shallow system.	Singhal (2008)
Urban groundwater pollution in alluvial aquifer	Ljubljana, Slovenia	Urban water balance modelling approaches, including UVQ, NEIMO, SLeakI/ POSI, and UL_FLOW	Sustainable urban development systems like on-site infiltration of roof runoff and improved sewer control and standards could result in better groundwater quality.	Vizintin et al. (2009)
Sewage leakage to surrounding groundwater and stormwater drains	Singapore (considering generic conditions)	Numerical modelling of COMSOL Multiphysics	The simulation results may help better understand the local-scale migration of sewage leakage.	Ly and Chui (2012)
The interaction between groundwater and urban infrastructure	Bucharest, Romania	A hydrogeological conceptual method	Human-made infrastructure elements such as sewer networks, water supply networks, and subway tunnels are identified as contributors to the disruption of the natural hydrological cycle, impacting substantial percentages of groundwater recharge and discharge.	Boukhemacha et al. (2015); Gogu et al. (2019)
Wastewater compounds in urban shallow groundwater wells corresponding to exfiltration probabilities of nearby sewer networks	California's central coast, USA	Groundwater sampling and GIS	The resemblance of groundwater to sewage increases with rising sanitary sewer exfiltration likelihood.	Lee et al. (2015)
Wastewater loss from sewers to saturated soil	Laboratory	experimental	Groundwater in the vicinity of sewer exfiltration leaks minimally dilutes wastewater concentrations.	Nikpay et al. (2015)
Simulation of pipe leakage in variably saturated soil	a synthetic case study	Numerical approach, including the pipe flow simulator HYSTEM-EXTRAN and the GWF simulator OpenGeoSys	Greater flow volume and longer duration in pipe operations result in increased leakage, with the timing of the peak having a minimal impact on the extent of leakage.	Peche et al. (2017)
Occurrence of wastewater indicators in shallow urban groundwater	California's central coast, USA	Spatially explicit model of exfiltration probability	Sanitary sewer databases and groundwater digital elevation data can be analysed to predict where pipes are probably leaking and contaminating groundwater.	Roehrdanz et al. (2017)
Evaluations on urbanisation influences on groundwater	Hanoi, Vietnam	MODFLOW and WetSpa	The contribution of municipal water supply and sewer systems to groundwater recharge was estimated at 15.4 %.	Tam and Nga (2018)
Analysis of urban infrastructure effects on groundwater	Knoxville, USA	Monitoring groundwater level	Sewer networks were identified as the most significant parameter influencing groundwater over the studied area.	Thompson et al. (2021)
Quantification of water and sewage leakages into a shallow aquifer	Kharkiv, Ukraine	Stable isotopes	Sewage leakage to the aquifer is 1.4 $Mm^3\ a^{-1}$, less in amount than water supply leakages, but induced nitrate and associated contaminants pollution risk of urban groundwater.	Vystavna et al. (2018)
Studying "urban karst" influences from groundwater–storm sewer networks interactions	Lisgar District, Canada	Monitoring of utility trench wells and dye tracing from storm sewer networks exfiltration tests	Urbanisation significantly influences shallow groundwater, particularly through exfiltration from storm sewer networks, as evidenced by distinct patterns of head variations in the aquitard that are unrelated to widespread surface infiltration.	Shepley et al. (2020)

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Table 2 (*continued*)

Subject	Study area	Approach	Conclusion	Reference
Sewer exfiltration in groundwater after earthquake	Kumamoto, Japan	Measuring pharmaceutical tracers	The effect of the earthquakes on sewer exfiltration is trivial, as the damaged sewer networks were quickly repaired.	Kobayashi et al. (2021)
SLR impacts on wastewater leakage to coastal waters and storm drains	Honolulu, Hawai'i	Field survey, geochemical tracers, and emerging organic contaminants (EOCs) analysis	SLR is inducing more threats to environment and human health.	McKenzie et al. (2021)

groundwater and surface water resources, including Oosting and Joy (2011). Most studies of sewer networks have had limited attention to groundwater, and they have considered the transportation of liquid waste (Lovett et al., 1997), predicting wastewater flow rates (Fernandez et al., 2009), managing sewer in-line storage control (Zhang et al., 2018a), and concrete corrosion in sewer networks (Zounemat-Kermani et al., 2020b). Moreover, one aspect of sewer networks with much attention has been the failure, condition assessment and pipe inspections (Ana et al., 2009; Anbari et al., 2017; Ariaratnam et al., 2001; Baah et al., 2015; Baik et al., 2006; Balekelayi and Tesfamariam, 2019; Berardi et al., 2009; Chughtai and Zayed, 2008, 2011; Davies et al., 2001; Elmasry et al., 2018; Ghavami et al., 2020; Hahn et al., 2002; Hawari et al., 2018; Hluštík and Zeleňáková, 2019; Koo and Ariaratnam, 2006; Laakso et al., 2018; Malek Mohammadi et al., 2019; Mancuso et al., 2016; Miles et al. 2007; Moselhi and Shehab-Eldeen, 2000; Najafi and Kulandaivel, 2005; Nam et al., 2019; Nguyen and Seidu, 2022; Roghani et al., 2023; Rokstad and Ugarelli, 2015; Roozbahani et al., 2013; Salman and Salem, 2012a,b; Shehab and Moselhi, 2005; Sousa et al., 2014; Syachrani et al., 2013; Tran et al., 2007; Van Nguyen et al., 2022; Vladeanu and Matthews, 2019a, b). In addition, groundwater quality aspect has also been delved into in some research (e.g. Afonso et al., 2020; Borst et al., 2013; Ellis and Revitt, 2002; Foppen, 2002; Gotkowitz et al., 2016; Hensen et al., 2018; Ishii et al., 2021; Khorasani et al., 2020; Maguire and Fulweiler, 2016; Mester et al., 2020; Reynolds and Barrett, 2003; Rojas-Gómez et al., 2023; Wolf et al., 2006).

In this section, we provide an overview of the selected case studies that have examined the relationship between groundwater and sewer networks, with an emphasis on GWI quantitative analysis.

4.1. *Quantitative analysis of GWI in sewer networks*

Depending on the considered zone of the aquifer, we suggest dividing the conducted research into two main categories, i.e. (1) phreatic (saturated) zone (Table 3), and (2) vadose (unsaturated) zone (Table 4). For the latter category, we specifically chose studies that are more pertinent to GWI in sewer networks. Numerous studies have delved into surface water infiltration in sewer networks, but they are not encompassed in this selection.

In both categories, the undertaken case studies illustrate a rising trend from 2001 to 2024, delineated into two periods: 2001 to 2015 with limited research and 2016-2024 marked by a substantial increase in the number of studies (Fig. 3).

4.1.1. *Objectives in the conducted research*

Various dimensions of GWI in sewer networks have been examined quantitatively in the case studies, considering both phreatic zone and vadose zone of the aquifers (Tables 3 and 4), including the following:

- GWI in sewer networks
- RDII in sewer networks
- Correlation between rainfall, inflow, infiltration, and sewage flow patterns
- Surface water pollution due to GWI in sewer networks
- Repairing damaged sewer networks and GWL
- Water cycle and water budget in urban environments
- Impacts of urban development and water management on CSOs under CC and population growth
- Seasonal fluctuations of GWI in sewer networks
- Locating areas susceptible to RDII, I/I, and GWI
- I/I in sewer networks considering snowmelt period
- GWI in sewer networks in cold climate conditions
- Rainfall, temperature, and sea level rise (SLR) impact on GWL and sewer networks
- CC impact on GWL and sewer networks

Greater attention has been directed towards GWI, often in conjunction with groundwater inundation and SLR, particularly in the phreatic zone. Conversely, in the vadose zone, there has been a tendency to explore a combination of GWI with stormwater, RDII, I/I, surface water inflow, and overland flow (Tables 3 and 4).

Tables 3 and 4 highlight the limited emphasis on temporal variations, such as monthly and seasonal fluctuations, of GWI in sewer networks as the primary focus of the studies. Additionally, there is limited literature addressing the spatial risk mapping of the studied areas. Contrarily, the research has primarily centred on coastal sewer networks due to SLR stress.

Multiple studies have evaluated the impact of existing pressures on GWL and sewer networks (Tables 3 and 4), for which, we propose dividing the external stresses into three groups (Fig. 4):

(1) Anthropogenic stresses, e.g. urbanisation, population growth, and LC/LU changes
(2) CC, e.g. SLR, precipitation extremes, and floods
(3) Natural phenomena, e.g. earthquakes, land subsidence, and landslides

A challenge faced by sewer networks involves unauthorised or improper connections, which is attributed to group (1) among the existing stresses. Lepot et al. (2017) assessed unauthorised connections and lateral infiltration in sewer networks using an experimental approach, employing an Infra-Red camera and 2D temperature mapping. The study concluded that the detection limit is extremely low, and quantifying lateral discharge is not feasible.

Road drains may be considered as urban infrastructures with high potential of groundwater recharge (Stephen et al., 2023). Although in arid environments road drains may be an opportunity to recharge aquifers, in wetter urban environments they may include challenges, among which is high risk of GWI into sewer networks. The rainfall-derived inflow from weeping tiles accounted for up to 85 % of the total RDII in the sanitary sewer networks (Jiang et al., 2019).

CC exerts incremental effects on the interaction between groundwater and sewer networks in urban areas. Geological hazards occur, especially by damaged sewer networks, e.g. sinkhole susceptibility (Kim et al., 2018), ground subsidence (Karoui et al., 2018), soil and groundwater erosion (Guo and Zhu, 2017), and road pavement collapses along with traffic safety hazards (Kuliczkowska, 2016).

4.1.2. *Investigated areas in the conducted studies*

The geographical distribution of the conducted studies reveals a predominant focus on coastal regions. Moreover, the United States of America (USA) and European countries emerge as the primary

Table 3
Studies concentrating on quantitative analysis of GWI in sewer networks in saturated zone.

Model (approach)	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
MODFLOW	GFLOW code	Simulation of groundwater flow, surface water flow, and a deep sewer tunnel system	Menomonee Valley Brownfield, USA	73 % of the recharge within the MODFLOW domain directs its flow into the Inline Storage System of the Milwaukee Metropolitan Sewerage District. Regarding the origins of infiltration into the ISS, 36 % comes from recharge within the model's domain, 45 % from lateral flow into the domain, and 19 % from surface water bodies.	Dunning et al. (2004)
	A set of approaches, including a root-zone model and a grid-distribution tool	Quantification of GWI in sewer systems, taking into consideration the historical water cycle	Copenhagen, Denmark	GWI into sewer systems stands at approximately 10 mm/year.	Jeppesen et al. (2011)
	Nonlinear regression method; Monte Carlo	Modelling infiltration of groundwater into sewer networks	Dresden, Germany	Factors like the infiltration rate and the conductivity of the backfill play a crucial role in computing the leak area.	Karpf and Krebs (2013)
	Storm Water Management Model (SWMM)	Factors contributing to the increased concentrations of Enterococcus Faecalis in surface water, considering GWI into damaged sewer networks	Hoboken, USA	The risk of infiltration exceeds 50 % in nearly half of the entire network, even with the lowest estimated water table.	Liu et al. (2018)
	Experimental analysis; urban surface hydrological model (URBS-MO)	Contribution of groundwater to sewer networks	Pin Sec, France	Annually, sewer networks drain approximately 42 % of the total volume of soil water from rainfall.	Rodriguez et al. (2020)
	SWMM	The impact of repairing a damaged sewer on the GWL	Hoboken, USA	Following sewer repairs, CSOs incidents would decrease and only happen during substantial precipitation. Anyway, the groundwater level may increase, ultimately causing groundwater inundation in the city's low-lying areas during high tide.	Su et al. (2020)
	Urban water budget model; GIS	Simulating shallow urban groundwater at regional and local scales	Detroit, USA	A hydraulic conductance of 0.0025 ((m^2/d)/m) was utilised for sewer pipes using the Drain package in MODFLOW. Groundwater discharge is attributed to sewer drains and evapotranspiration. The local model incorporates the hydraulic conductance and bottom elevation of sewer lines, illustrating the interaction between groundwater and the sewer line system. The varied flow directions at local and regional scales signify the impact of urban configurations on groundwater dynamics.	Teimoori et al. (2021)
	Field surveys for gathering hydrological data	Impact of rising sea levels on recurrent flooding caused by groundwater in a coastal urban region with aging infrastructure	Hoboken, USA	The model considers the interplay between the aquifer and deteriorating water infrastructure, which can both deplete the aquifer (GWI) and introduce water (leakage from drinking water systems). Higher-than-anticipated hydraulic conductivity in the northwestern region of the domain is attributed to the existence of utilities and infrastructure beneath the urban area, potentially forming preferential pathways for groundwater flow along walls.	Su et al. (2022)
	Digital Elevation Model (DEM); PCSWMM model; GIS	Simulation of compound flooding effects of seawater, groundwater, and stormwater sources on coastal drainage infrastructure under CC	Imperial Beach, USA	While marine inundation alone is projected to affect only 7 % of the study area by 2100 under the most pessimistic scenario (a 2-meter rise), findings reveal that over 20 % of the subterranean	Sangsefidi et al. (2023a)

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Table 3 (*continued*)

Model (approach)	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
				storm drain system in the study area is currently susceptible to subsurface flooding at existing sea levels.	
	Personal Computer Storm Water Management Model (PCSWMM); GIS	CC impacts on coastal groundwater and sanitary sewer infrastructure	Imperial Beach, USA	The sea level rise-induced groundwater shoaling is expected to impact 36 % of the underground sewer networks. As a result of GWI and RDII, the flow of sanitary sewage increases by 21% during DWCs (consecutive days without precipitation) and 49 % during WWCs (a 24-hour rainfall event with a 25-year return period).	Sangsefidi et al. (2023b)
FEFLOW	URBS hydrological model; HYDRUS 1D	Introducing an approach representing interactions between surface hydrology, groundwater, and underground structures in hydrological models	a hypothetical watershed	The work outlines the creation, assessment, and incorporation into the urban hydrological model URBS of a series of modules intended to represent the urban subsurface realm in shallow groundwater conditions.	Pophillat et al. (2021)
HydroGeoSphere (HGS)	GIS	Impact of water infrastructure on groundwater and surface water	Laurel Creek Watershed, Canada	GWI into sewer networks is 36.30 %, which is close to the real measurement result of 30.82 %.	Guo (2017)
MIKE SHE	MIKE URBAN	Simulation of the entire freshwater cycle within the urban environment	Silkeborg, Denmark	One quarter of the water input into the stormwater runoff systems originated from groundwater sources. The study quantifies how forced infiltration influenced the local groundwater level, resulting in an average increase of up to 69 cm.	Kidmose et al. (2015)
	MIKE URBAN	GWI into sewer networks	Frederikshavn, Denmark	Considering a scenario with no GWI to sewer networks, water table would rise to a depth less than 5 m below ground level.	Thorndahl et al. (2016)
	Geological and hydrological models	Influence of urban geology and spatial discretisation on the simulation of shallow groundwater levels and flow paths	Odense, Denmark	Although subsurface infrastructure and fill material occupy a small fraction of shallow geology, they significantly affect the simulation of local water levels and alter flow paths, e.g. less recharge to deeper aquifers and an increased percentage of particles flowing to saturated-zone drains and leaky sewer pipes.	LaBianca et al. (2023)
HYSTEM-EXTRAN	PCGEOFIM; TrimR2D (Transient Inundation Model for Rivers-2 Dimensional); RisoDGM software	Main water fluxes and interactions between surface flooding, sewerage, and groundwater	Saxon capital of Dresden, Germany	The contrast between groundwater inflow into sewerage and loading from floodwater infiltration reveals that infiltration of surface floodwater is the primary cause of sewerage overloading. Simultaneous rainfall events can exacerbate the issue. The impact of sewerage water distribution on groundwater rise is localised.	Sommer et al. (2009)
	-	GWI, surface water inflow and sewerage exfiltration seeing hydrodynamic situations	Dresden, Germany	Contrasting the GWI from steady-state and dynamic calculations reveals a comparable peak infiltration rate. However, the dynamic simulation exhibits a delayed rise and fall of the infiltration rate because of a faster increase in the in-sewer water level preceding the peak.	Karpf et al. (2011)
Analytical (empirical) solutions	Nonlinear reservoir algorithm	Groundwater intrusion into leaky sewer networks	Lower Saxony and Baden-Württemberg, Germany; Terkos Lake watershed, Turkey	While wastewater flows exhibit relatively consistent year-round patterns, the separated groundwater flows display declines and seasonal fluctuations that correlated with baseflow in nearby rivers. Analysing the	Wittenberg and Aksoy (2010)

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Table 3 (*continued*)

Model (approach)	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
				recession characteristics of influents at treatment plants enables the quantification and prediction of groundwater intrusion into sewer networks.	
	GWI Potential (GWIP), considering the elevation of the groundwater level with the position of the sewer conduits; Voronoi polygonation (diagram)	Analysing the source of dilution of wastewater	Flanders, Belgium	GWI into sewer networks is prone to occur in flat regions with a naturally shallow phreatic groundwater level, whereas it is expected to be less prevalent in more hilly areas.	Dirckx et al. (2016)
	Wastewater production method; minimum flow factor method; Stevens–Schutzbach method	Calculating groundwater and rainfall infiltration into sewer networks	Rasht, Iran	A base infiltration of about 20 % into sewer networks was estimated.	Neshaei et al. (2017)
	Darcy's Law	GWI to coastal sewer networks	Pearl, USA	The study underscores the growing significance of sea level rise's effects on GWI in coastal collection systems, emphasising the need for their inclusion in facility planning and design.	Budd et al. (2020)
	A modelling equation; Nonlinear reservoir model	Impact of urban development strategies and water management on CSOs under CC and population growth	Nantes, France	Specific scenarios indicate that population growth and urban development may have a more significant impact on overflows compared to the potential effects of CC.	Mahaut and Andrieu (2019)
	Sanitary Sewer Overflow Analysis and Planning (SSOAP) software; cross-correlation statistical analysis; a 2-dimensional model (equation)	GWI into coastal sewer networks considering sea level rise	Pearl, USA	The average effective defect anticipates a surge in GWI ranging from 70 % to 200 % with sea-level rise increments of 0.3 to 0.9 m for presently submerged pipes. The projected additional GWI for pipes expected to be submerged as a result of sea-level rise could elevate GWI to levels approaching or surpassing the current average DWCs.	Fung and Babcock (2020)
Water balance	-	Groundwater balance variations in the context of leaking water mains and GWI to sewer networks	Major cities, Japan	Between 4 % and 54 % of total flow in sewage was attributed to GWI.	Yasuhara (2004)
	Pollutant mass flux; continuous water quality and quantity monitoring	Computing of GWI into sewer networks	Prague, Czech Republic	The findings highlight a substantial contribution of parasitic waters to the minimal discharge during nighttime. The measured I/I are noteworthy, constituting 45 % of the average daily discharge.	Bareš et al. (2009)
Hydrograph separation	Oxygen isotopes	Calculating the infiltrated water into sewer networks	Torraccia and Infernetto, Italy	Infiltration from groundwater and drinking water was estimated to be 14 % for Torraccia and 50 % for Infernetto.	Prigiobbe and Giulianelli (2009)
	USEPA SSOAP model; RTK unit hydrograph method; regression analysis (JMP software); GIS	The effect of sewershed characteristics on I/I into sewer networks	Milwaukee, USA	Infiltration, characterised by gradual inputs from groundwater sources, exhibits a negative correlation with imperviousness, pipe length, low intensity, and medium intensity land use.	Sebo and McDonald (2022)
	Sanitary Sewer-Width Function Instantaneous Unit Hydrograph (SS-WFIUH) approach	Wastewater flow modeling and I/I simulations	Northern Virginia, USA	GWI ratio in sewer networks is between 7.8 % and 9.4 % of the total sewage flow for COVID and pre-COVID periods, respectively.	Perez et al. (2024)
Statistical analysis	Statistical analysis of Closed-Circuit Television (CCTV) inspected sewers; SIMBA sewer simulation	The relation of sewer networks status and the infiltration rate	Dresden, Germany	80 % of extraneous waters enter the sewer networks in large diameter pipes.	Schulz et al. (2005)
	Geostatistical approach; spatial analysis of data; cross-correlation analysis	Impact of GWL variations on sewer networks	Bordeaux, France	Coupling the spatial maps with sewer networks depth allowed establishing network vulnerability maps linked to the groundwater presence and its behaviour.	Marache et al. (2006)
	Regression analysis; hydrograph analysis; Darcy's law	Quantification of I/I in urban sewer networks	Dresden, Germany	With a ratio of 74 % of the total I/I volume, GWI was recognised as the most important contributor to I/I in the study.	Karpf et al. (2007)

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Table 3 (*continued*)

Model (approach)	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
GIS	R software	Groundwater inundation due to interactions between sewer infrastructure and global change	Philadelphia, USA	Groundwater inundation was announced as probable considering aging sewer infrastructure. Plus, altered groundwater flow dynamics caused by sea level rise and CC will likely stress aging sewer infrastructure, leading to increased discharge of CSOs systems and flooding.	Rossi and Toran (2019)
Machine learning	Statistical approach; decision-support model; logistic regression	GWI into sewer networks	Hoboken, USA	After calibration, the model's predictions closely match measurements with an accuracy rate of 82 %. Sensitivity analysis reveals groundwater level as the most critical parameter.	Liu et al. (2021)
Tracers	-	Estimating infiltration rates in sewer networks	Lyon, France	Infiltration flow rate was announced to change from 15 m^3/hour to 40 m^3/hour.	De Bénédittis and Bertrand-Krajewski (2005b)
	Artificial sweetener acesulfame; Monte Carlo chemical mass balance approach; a physically based numerical self-optimisation model using a microbial genetic algorithm	Source and volume of groundwater entering the urban sewer networks	Chaohu, China	In the study area, 7.9 % of the sewer length is responsible for 58 % of the total GWI. Diurnal fluctuations in groundwater seepage into the sewer networks are closely related to in-pipe water levels associated with the operation mode of sewage pumps, underscoring the significance of regulating in-pipe water levels in controlling GWI. In comparison to traditional visual inspection or direct flow measurement methods, the proposed approach offers distinct advantages for identifying groundwater sources and flows in extensive sewer networks.	Zhao et al. (2020)
	Noble gases; miniRuedi as a portable mass spectrometric system	GWI in the sewer networks	Dübendorf, Switzerland	GWI ratio estimated ranges from 40 % to 80 %. The accuracy of the estimation results is greatly affected by uncertainties in water and noble gases sampling. The presented GWI ratio may be systematically biased due to the strong assumption regarding gas exchange and the associated gas loss factor.	Zhu (2022)
	Stable isotopes	Calculation of extraneous discharge of groundwater in combined sewer networks	Rümlang, Switzerland	GWI contributes 39 % of the total daily wastewater discharge in DWCs.	Kracht et al. (2007)
	Stable isotopes; pollutant time series method; minimum night flow; water balance	Calculation of extraneous discharge of groundwater in combined sewer networks	Rümlang, Switzerland	GWI is estimated to differ from 683 m^3 (37 %) to 786 m^3 (43 %).	Kracht et al. (2008)
	Hydrogeochemical approach; water budget	Seasonal properties of water infiltration into sewer networks	Brussels, Belgium	The volumes of infiltrated clear water amount to approximately 120 m^3/day during the winter when the water table is elevated, decreasing to around 40 m^3/day in the summer.	De Ville et al. (2017)
	Lithium tracer tests; water mass balance; monitoring sewage flow and quality	Exfiltration and infiltration influences on sewage discharge and quality	Hue, Vietnam	The calculated infiltration represents 11 % and 62 % of the overall sewage inflow into the sewer during dry and rainy seasons, respectively. Exfiltration ratios for the dry and rainy seasons are 65.6 % and 24.0%, respectively. Only 23 % of the water supplied to the area reaches the sewer outlet in the dry season, while 123 % flows in the rainy season.	Watanabe et al. (2021)
	Stable water isotopes; wastewater sampling	GWI in sewer networks in cold climate conditions	Oulu, Finland	Because of the climate conditions (lack of surface water inflow), the GWI into the monitored network	Heiderscheidt et al. (2022)

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Table 3 (*continued*)

Model (approach)	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
				branch accounted for the entirety of infiltration/surface inflow flows and was assessed to peak at a maximum daily rate of 6.5 %. This is significantly lower than the reported yearly average infiltration/surface inflow rate of approximately 29 % for the city's network.	
	Stable isotopes; flow and temperature monitoring	Quantification of I/I in sewer networks in cold climate conditions	Oulu, Finland	Using different approaches, I/I was quantified to vary from 1.5 % to 35 %.	Tesfamariam et al. (2024)
Hydrogeochemical analysis	Groundwater sampling; fluorescence spectroscopy for dissolved organic matter sewage; mass balance method, considering total phosphorus and $NH4^{+}$ -N; parallel factor analysis using MATLAB and DOMFluor toolbox	GWI in sewer networks	Shantou, China	Groundwater component in the examined wells along the pipeline network varies from 10.8 ± 2.5 % to 9.6 ± 3.5 %, falling within the acceptable limits for municipal sewage pipelines (10–15 %).	Li et al. (2023b)
Field Surveys	Flow monitoring data and rainfall data; SSOAP Toolbox, a computer software; DWCs	System characterisation report	North Hudson, USA	GWI is estimated to differ from 0.058 to 1.103 million gallons per day.	North Hudson Sewerage Authority (2018)
	Measuring flow rates; flowmetres to determine the hydrograph of wastewater flow	Quantifying RDII, GWI, and total I/I within sanitary-sewer pipes	Atlanta, USA	The GWI generally exceeds RDII and infiltration by an order of magnitude, varying between 24 and 41 mm per year across watersheds with an annual stream discharge of approximately 500 mm.	Pangle et al. (2022)

contributors to research in this context (Fig. 5). Proximity to the shoreline, susceptibility to CC and SLR, along with shallow GWL, particularly prevalent in European countries, can be identified as the primary factors contributing to this phenomenon. However, the authors posit that even in these regions, there is a shortage of sufficient and more comprehensive studies on GWI in sewer networks.

Taking into account both saturated and unsaturated zones, limited diversity exists in the spatial scales of the studies, especially on regional and larger scales (Tables 3 and 4).

4.1.3. *Methodologies employed in the conducted studies*

Given that many studies on GWI in sewer networks have taken place in coastal urban settings, there is a multidisciplinary aspect, encompassing various types of models and data. Data may include hydrological, hydrogeological, sewer-related, social, and demographic data (Fig. 6). Plus, numerous calibration criteria may be included, e.g. hydraulic head, surface water fluxes, vertical gradients, and GWI into the sewer networks (Dunning et al., 2004). GWL (Budd et al., 2020; Cahoon and Hanke, 2019) and the hydraulic conductivity of the surrounding soil (Liu et al., 2021) have been considered as crucial input parameters. Moreover, other data may have significant effects on the generation of extraneous flows, e.g. rainfall, temperature, and sea level (Cahoon and Hanke, 2019).

A model might seek to have the ability to integrate the surface and subsurface processes dynamically, in addition to including both overland and sewer drainage. As asserted by LaBianca et al. (2023) MIKE SHE, ParFlow coupled with the Common Land Model (CLM), MODFLOW 6, and HydroGeoSphere offer these capabilities. We have classified the approaches utilised in the conducted case studies within the phreatic zone (Table 3) and vadose zone (Table 4) of the aquifers. It is noteworthy that, in many cases, a combination of modelling methods has been investigated. Consequently, the primary approach and additional methods have been extracted from the literature. Different approaches have dissimilar capabilities, e.g. some approaches may efficiently assess the operational status and overflow risk of sewer networks in real-time during rainy seasons (Huang et al., 2023).

Examining the phreatic zone of the aquifer (Table 3), numerical approaches, particularly MODFLOW, have been extensively employed as the primary model. Additional numerical methods encompass MIKE SHE, HYSTEM-EXTRAN, FEFLOW, and HydroGeoSphere (HGS). Following numerical approaches, tracers, including hydrogeochemical methods, have been consistently chosen as the primary approach. Analytical (empirical) solutions emerge as the next most prevalent. Other considered approaches encompass statistical analysis, water balance, hydrograph separation - separating DWCs and WWCs- field surveys, geographic information system (GIS), and artificial intelligence (AI).

In contrast, when scrutinising the vadose zone of the aquifer (Table 4), numerical approaches have been utilised sparingly, with field surveys being the predominant method. Subsequent to field surveys, frequently employed methods include water balance, hydrograph separation, statistical analysis, hydraulic solutions, and analytical (empirical) examinations. Tracers, GIS, and AI, despite their high potential in water sciences, have received limited attention, mirroring the situation in the saturated zone for the last two items.

Kretschmer et al. (2008) categorised approaches into quantitative and qualitative methods. The former includes hydraulic and chemical methods, while the latter involves visual methods and the interpretation of hydrograph curves. Qualitative approaches were deemed to be more precise, although they often require labour-intensive data collection, entailing a certain financial investment.

In comparison to conventional flow-based methods, the conductivity-based method offers distinct advantages in estimating RDII and overflow, particularly when these two processes occur simultaneously (Zhang et al., 2018b, c). Compared to traditional visual inspection or direct flow measurement methods, the approach proposed by Zhao et al. (2020), i.e. chemical tracer in conjunction with physically based optimisation model, offers distinct advantages for identifying groundwater sources and flows in extensive sewer networks. For insights into the measurement methods of I/I of non-sewer water into urban sewer networks, De Bénédittis and Bertrand-Krajewski (2005a) cover conventional methods, while Beheshti et al. (2015) discuss both

Table 4
Studies focusing on quantitative analysis of GWI in sewer networks in vadose zone (primarily with an emphasis on RDII).

Approach	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
Field surveys	Time series of pollutant loads and discharged wastewater volume; the chemical hydrograph separation of wastewater discharge; automated sensors; AQUASIM	Quantification of infiltration into sewer networks	Uster and Rümlang, Switzerland	Infiltration ratio into sewer networks is estimated to be 62–65 % for Uster and 35–38 % for Rümlang.	Kracht and Gujer (2005)
	Daily flow data; dilution rate; population specific flow	The impact of I/I on wastewater treatment plants	Sweden	The median dilution does not vary very much between the wastewater treatment plants, ranging from 130 to 230 % of the wastewater flow.	Hey et al. (2016)
	Flowmeters equipped with ultrasonic sensors; rain gauges	Correlation between rainfall, inflow, infiltration, and sewage flow patterns	Kuantan, Malaysia	The average infiltration rates of Q_{peak} and Q_{ave} are 17 % and 21 %, respectively, surpassing the earlier values of 5 % and 10 %.	Yap and Ngien (2017); Yap et al. (2017)
	Fiber-optic distributed temperature sensing	Measuring extraneous water I/I into sewer networks	Trondheim, Norway	The application of the method in quantifying real-life, RDII and inflow into the sewer networks is approved.	Beheshti and Sægrov (2018)
	Conductivity-based method	Quantifying RDII in sewer networks	Wuxi City, China	The approach distinguishes between rainfall-derived inflow and rainfall-induced infiltration by leveraging conductivity data.	Zhang et al. (2018b)
	Fiber-optic distributed temperature sensing; closed-circuit television inspection; smoke testing	Extraneous water ingress into the sewer networks	Trondheim, Norway	I/I of extraneous water in separate sewer networks during a period without snowmelt or GWI is detected.	Beheshti and Sægrov (2019)
	Distributed temperature sensing	Characterising I/I into sewer networks before, during and after snowmelt period	Skellefteå, Sweden	During snowmelt, several locations with I/I are identified, while the locations do not show I/I during storm events after the snowmelt. In addition, during a very heavy storm after the snowmelt period, I/I is found at other locations.	Panasiuk et al. (2019)
	THWater Smart Drainage Monitoring Flowmetre	I/I assessment of sewer networks	Ningbo, China	The fraction of monthly averaged GWI to total flow can be up to 70 % primarily because of the elevated water table.	Ye et al. (2023)
Tracer	Mass flux method; water quality monitoring using in-line absorption spectrometry; wastewater hydrograph analysis; Monte Carlo	Evaluation of I/I of parasitic water to wastewater treatment plant	Prague, Czech Republic	I/I contributes approximately 34 % of the total wastewater treatment plant inflow.	Bareš et al. (2012)
	Mathematical methods; FLEATRAP software	Analysing the source of dilution of wastewater	Flanders, Belgium	Over half of the flow during DWCs was attributed to dilution.	Dirckx et al. (2009)
Empirical (analytical)	Triangle and moving-minimum methods	Analysis of I/I within combined sewer networks	Germany	Valuable insights into water pathways in urban hydrology are provided. In addition, it is highlighted that I/I adversely affect the drainage system's performance	Weiß et al. (2002)
	Darcy's Law	I/I, including GWI and surface water inflow, within sewer networks	Dresden, Germany	Both GWI and year of construction are identified as significant indicators for estimating the infiltration potential of sewer pipes.	Karpf and Krebs (2011)
	Annual water consumption and sewage discharge balance; triangle method; minimum night flow method; moving minimum method; analysis of sewage supply to wastewater plant in DWCs and WWCs	Assessing the amount of extraneous water inflow to the sewer networks	North-western Poland	Portion of infiltration differs from 18 % to 68 %, contingent upon the year and the method used.	Bogusławski et al. (2022)
Water balance	Monitoring a network of piezometers for three years	Tracking the fate of infiltrated stormwater in an infiltration basin	Wicks Reserve Infiltration Basin, Australia	Sewer networks and stream interact with the upper portion of the stormwater plume that have infiltrated, causing a local reduction in the water table.	Bonneau et al. (2018)
	Dilution method; water balance method	I/I to wastewater systems	Norway, Sweden, Denmark, and Finland.	I/I are decreasing for Norway and Sweden, while stable for Denmark and Finland.	Jenssen Sola et al. (2018)
	Flow surveys and flow balance analysis	Stormwater ingress into sanitary systems	Jiaxing, China	I/I contribute to the ingress of stormwater into the sanitary system, resulting in external flows.	Tan et al. (2019)
	Balance model of water flow and pollutant loads	Quantifying extraneous water and organic matter degradation in sewer networks	Lake Erhai, China	Findings indicate that approximately half of the combined sewage collected by systems is attributed to extraneous water. Nevertheless, the GWI per unit length remains within the design specifications, and the relatively	Yang et al. (2021)

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Table 4 (*continued*)

Approach	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
				elevated proportion of extraneous water is primarily associated with the limited total amount of sewage discharge in the study area.	
	Water-budget approach; principal component analysis; multiple-linear regression	Quantifying the magnitude of I/I throughout 90 watersheds	Atlanta, USA	Findings indicate that I/I play a significant role in the overall outflow within urban watersheds, with its mean annual value comprising 25 % to 40 % of stream discharge. Regression analyses highlight that the density of older housing, serving as a proxy for deteriorating sewage infrastructure, emerges as the most crucial predictor of I/I throughout the Atlanta region.	Diem et al. (2022)
Hydrograph separation	Filtering method (Separating DWCs and WWCs)	Infiltration flow quantification of different subflows in wastewater	Flanders, Belgium	Satisfactory results are achieved for monthly and yearly averages, but daily accuracy is somewhat compromised. This filtering technique can be applied to assess which combined sewer networks experience significant levels of undesired flows.	Vaes et al. (2005)
	Separating DWCs and WWCs; cross-correlation analysis; linear regression model	Modelling surface inflow and GWI into sanitary sewers	Southern Pinellas County, USA	In the sub-sewershed with the shallowest GWL and the highest amount of submerged sanitary sewer infrastructure, an average of 56 % of the average daily flow comprises groundwater, as opposed to 44 % for the entire study site.	Long (2017)
	Surf-2D; unit hydrograph method; SWMM	Rainfall–runoff–infiltration process on overland flow and its interactions with sewer networks	Greenfield, UK	Sandy loam, results in a reduction of generated surface runoff to 36 %. Conversely, clay loam leads to a decreased runoff, specifically to 27 %. These findings underscore the significance of soil type in determining overland flow, as it governs the limits of infiltration capacity.	Martínez et al. (2021)
	Decomposition and quantification of the effluent flow from total waterflow (separating DWCs and WWCs)	Calculating inflow in sewer networks	Folhadela, Portugal	15 % of wastewater at the studied area is domestic wastewater, and the remaining 85 % originates from extraneous flow.	Bentes et al. (2022)
	Decomposition and quantification of the effluent flow from total waterflow (DWCs and WWCs)	Effects of inflow, infiltration, and exfiltration on sewer networks	Tehran, Iran	The findings reveal a cumulative annual increase of 158.674 million cubic metres in the water footprint within the Tehran sewerage system attributed to infiltration, inflow, and exfiltration. Over 85 % of this volume results from untreated wastewater discharged into the environment.	Rezaee and Tabesh (2022)
Statistical	Basic regression model with autoregressive errors	Flow data, I/I ratio, and autoregressive error models	Charlotte, USA	An approach is introduced in order to support statistical inferences with respect to the level of RDII.	Zhang (2005)
	Analysis-of-variance (ANOVA)	Towards more efficient infiltration measurements	Dresden and Emscher, Germany	It is estimated that the optimisation potential amounts up to 30 % accuracy improvement compared to non-optimised gauge distributions.	Franz and Krebs (2006)
	Multiple regression analyses; gravity collection methods	Impact of rainfall, temperature, and sea level on the I/I in coastal wastewater collection systems	North Carolina, USA	Rainfall, temperature, and sea level are deemed significant on the generation of extraneous flows for approximately 95 %, 95 %, and 58 %, respectively, with GWL being a significant driver of further deterioration of infrastructure.	Cahoon and Hanke (2019)
	Linear regression analyses with bootstrapping methods	Quantifying rainfall-derived inflow from private foundation drains in sanitary sewer networks	London, UK; Ontario, Canada	The rainfall-derived inflow from weeping tiles accounted for up to 85 % of the total RDII in the sanitary sewer networks.	Jiang et al. (2019)
	Regression	Differentiate I/I in sanitary sewer networks	City of South Salt Lake, USA	The model can help the practitioners separate I/I from other wastewater flows, customise measures to control I/I, and improve sewer networks performance.	Sowby and Jones (2022)
GIS	Geostatistical approach	Locating RDII into wastewater treatment systems	Minneapolis, USA	Locations with significant rates of I/I, due to high magnitude precipitation events, are located throughout the study area.	Williams (2017)

(*continued on next page*)

Table 4 (*continued*)

Approach	Other approach(es)- if used	Subject	Study area	Conclusion	Reference
	Including the sewer networks and the hydrologic soil classifications	A qualitative approach to determine the areas susceptible to I/I	Youngstown, USA	The approach employed in this study streamlines the scope of the task by generating a map that identifies areas with the highest susceptibility.	Thapa et al. (2019)
Performance indicators	Sewer networks characteristics, infiltration, and exfiltration measurements campaigns	Assessing the impact of infiltration and exfiltration in sewer networks	Yzeron and Ecully, French; Torraccia, Italy	The contribution of infiltration differs from 18 % to 300 %, corresponding to 15 % to 55 % of the DWCs.	Cardoso et al. (2006)
Artificial intelligence technology	Adaptive neurofuzzy inference system (ANFIS); multilayer perceptron neural (MLPN) network	Comparative analysis of artificial intelligence models in detecting potential I/I in sewer networks	Espoo, Finland	Adaptive neuro-fuzzy inference system demonstrates superior performance compared to the multilayer perceptron neural network in modelling the I/I situation.	Zhang et al. (2020)
Physically-based	COMSOL Multiphysics software	Influence of stormwater infiltration on RDII	Milwaukee, USA	RDII contributes to 73–79 % of the total volume of the sanitary sewer flow and constitutes 21 % of the overall water balance in the sewershed. Furthermore, the surface-based direct inflow is more significantly influenced by the precipitation/ evapotranspiration ratio, whereas subsurface infiltration is primarily controlled by the depth of the water table and the density of defects in the sewer networks.	Zhang and Parolari (2022)
Hydraulic	Measuring flow campaigns; hydrographical curves; average monthly DWCs; balance of drinking water consumption and wastewater quantity; method of the nocturnal minimum; method of daily average; method of annual wastewater quantity; triangle method; method of sliding minimum	Monitoring flow and infiltrated water in sewer networks	-	The infiltration water loading (infiltration water flow related to DWCs) is calculated to be between 18 % and 82 %.	Kretschmer et al. (2008)
	InfoWorks ICM (a hydrodynamic, integrated catchment, decision-making model)	Assessing the dilution of sewage	Flanders, Belgium	Additional water accounts for a 5–35 % increase in CSOs volume. The impact on treatment plants appears less substantial, with minor improvements in treatment efficiency (2–4 %). Energy savings (up to 5 %) only slightly surpass the increase in sludge production costs, assuming the elimination of this extraneous water.	Dirckx et al. (2019)
	Developing a customised hydraulic model using Microsoft Excel and GIS	Sewer I/I in catchments with high rainfall and aging infrastructure	Gordonvale, Australia	The specially devised sewage estimation method effectively anticipates sewage flows during the trial periods. It successfully identifies sources of I/I, pinpointing aging, and faulty sewage infrastructure as the primary contributing factor, with particular concern for GWI.	Keily (2019)
	Surface overflow and underground infiltration (SOUI) model; SWMM; computer vision; U-Net model; continuous genetic algorithm optimization (CT-GA) model; spatial interpolation; water balance model; field surveys	Computing the surface overflow and underground infiltration in sewer pipes	Fuzhou City, China	In comparison to the SWMM simulation, the precision of water level simulation improves by 43.5 % during rainfall, and the computational optimization reduces time costs by 67.5 %. The suggested approach can efficiently assess the operational status and overflow risk of sewer networks in real-time during rainy seasons.	Huang et al. (2023)

conventional and advanced techniques.

4.1.4. *Key findings from the conducted studies*

4.1.4.1. Proportion of GWI in sewer networks. Key findings of different studies are presented in Tables 3 and 4. The proportion of GWI in sewer networks has been studied in various literature, as illustrated in Fig. 7. This ratio varies significantly, ranging from 7 % (Oulu, Finland), to 70 % (Ningbo, China). Leakage from water mains and GWI into the sewer networks are identified as the primary influencing factors on the groundwater balance in certain major cities in Japan (Yasuhara, 2004).

GWI may be the most important contributor to I/I (Karpf et al., 2007) or fall within the acceptable limits for municipal sewage pipelines, e.g. 10–15 % (Li et al., 2023b). This is only regarding GWI, as larger amounts may be contributed to sewer networks from I/I, e.g. 85 % as estimated by Bentes et al. (2022). Simultaneous rainfall events can also exacerbate the issue (Sommer et al., 2009).

4.1.4.2. Temporal variations of GWI in sewer networks. The findings highlight a substantial contribution of GWI to the minimal discharge during nighttime (Bareš et al., 2009). Diurnal fluctuations in GWI into the sewer networks may be closely related to in-pipe water levels associated with the operation mode of sewage pumps, underscoring the significance of regulating in-pipe water levels in controlling GWI (Zhao

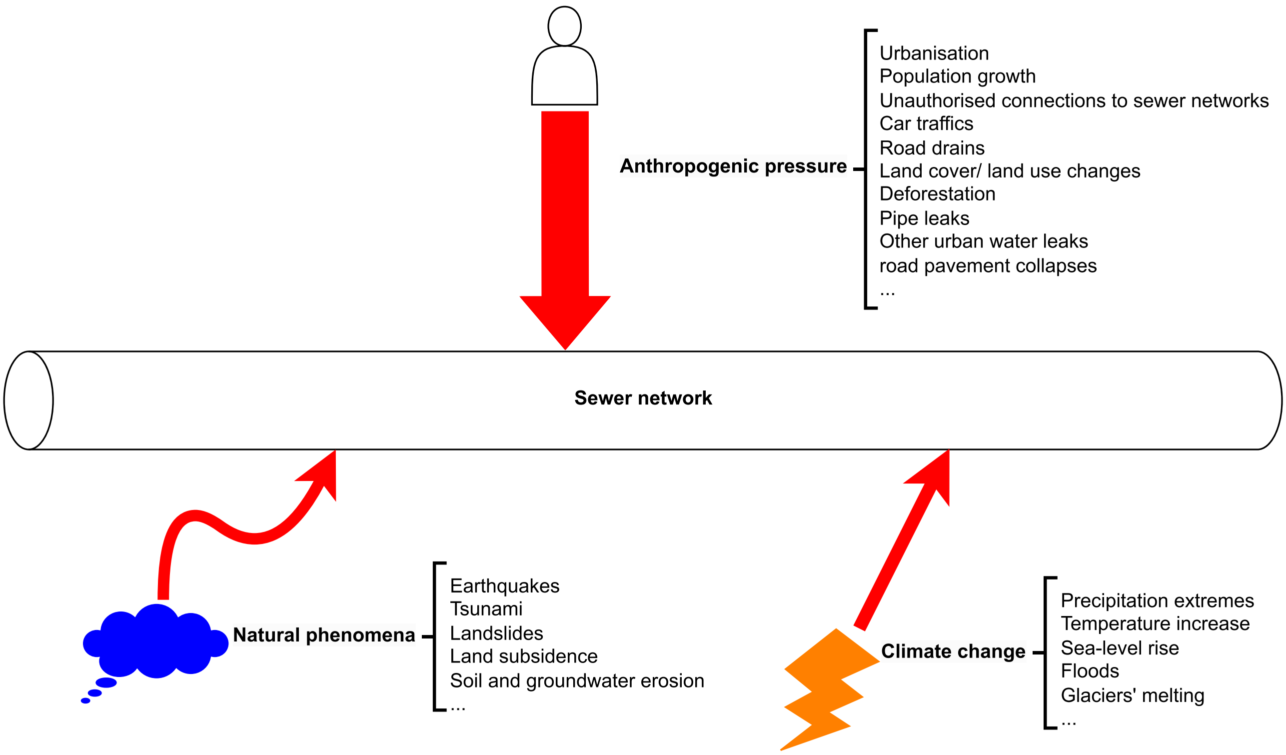

Fig. 4. Spatial distribution of case studies examining GWI in sewer networks.

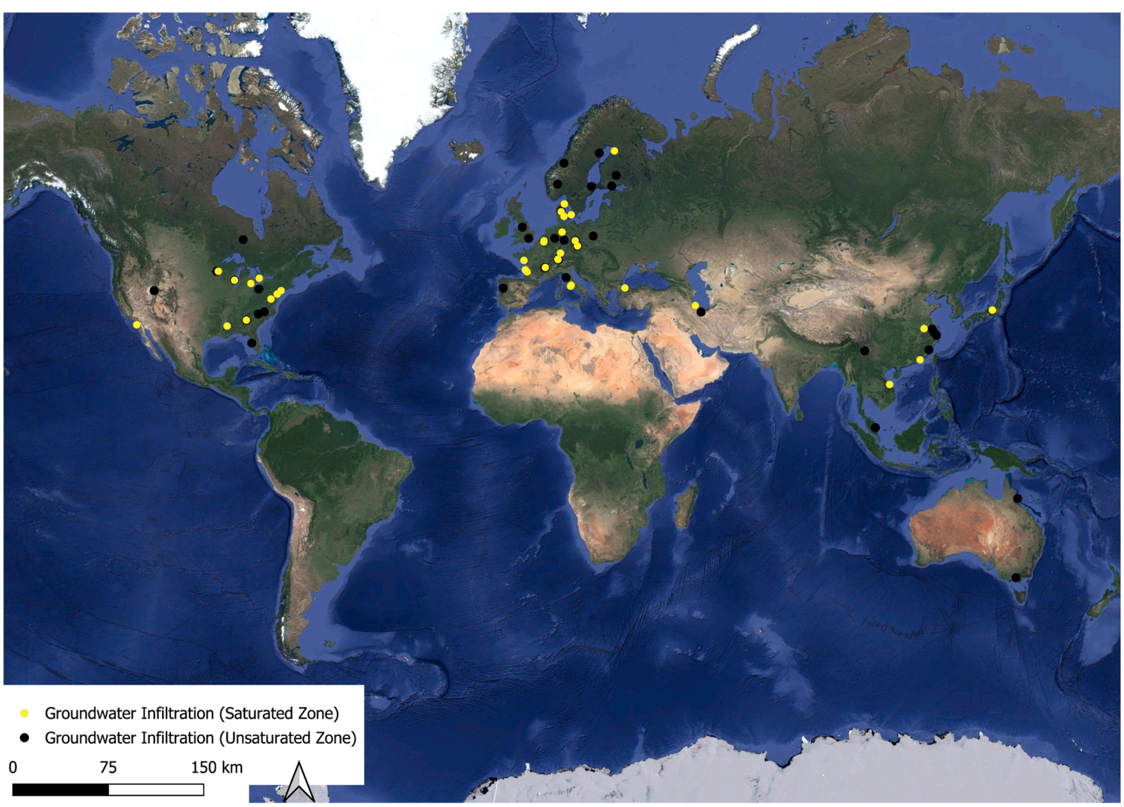

Fig. 5. Different stresses on sewer networks.

et al., 2020). In addition, contingent upon the year and the method used, the portion of infiltration may differ (Bogusławski et al., 2022). Satisfactory results may be achieved for monthly and yearly averages, but daily accuracy may be somewhat compromised (Vaes et al., 2005). The peak and nadir levels of GWI can be ascribed to the winter (characterised by a raised water table) and summer (marked by a lower water table), respectively (De Ville et al., 2017). Sewerage exfiltration presents the inverse pattern (Watanabe et al., 2021). The seasonality of I/I and

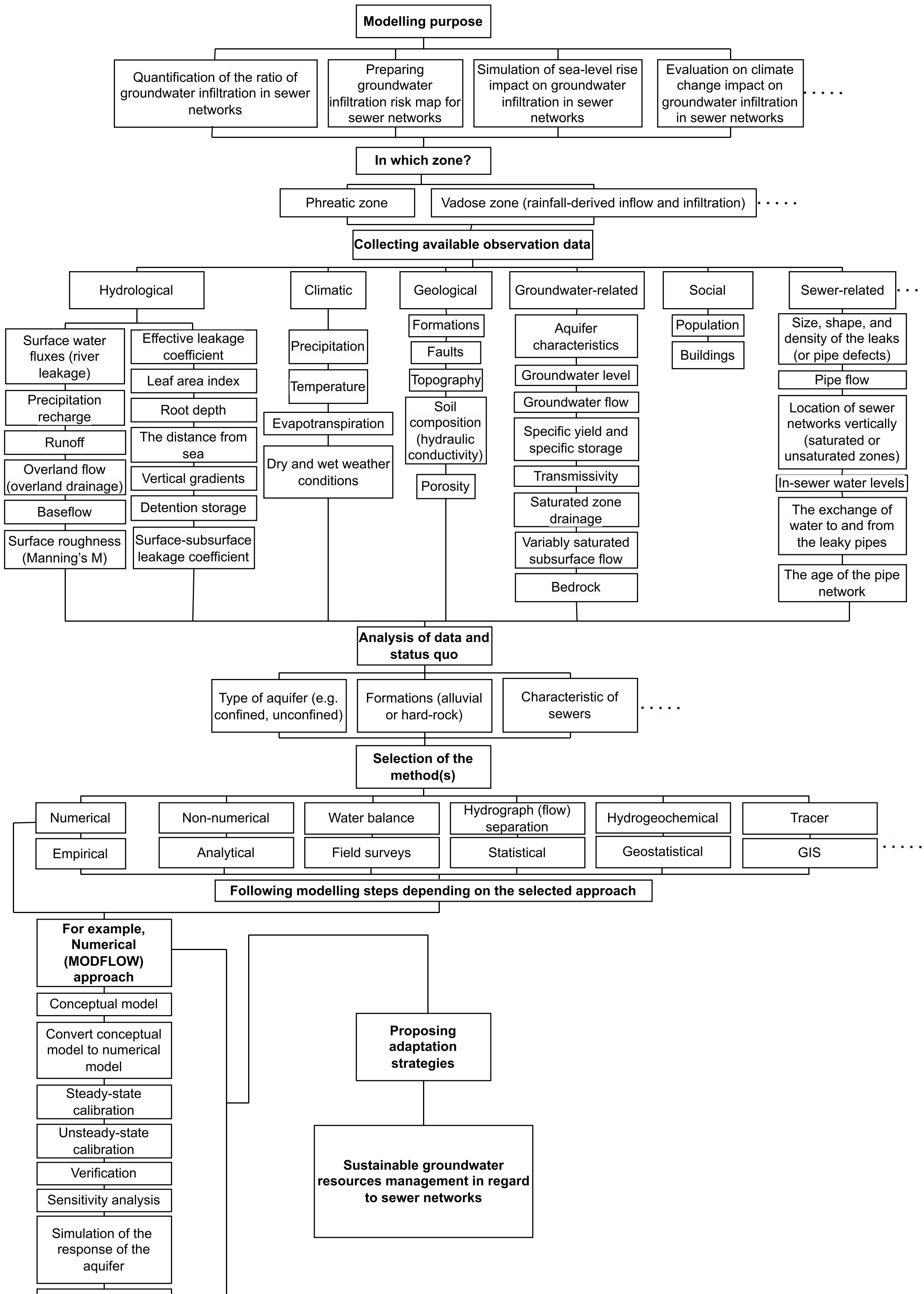

Fig. 6. A proposed methodology along with various data which may be used for quantitative analysis of GWI in sewer networks.

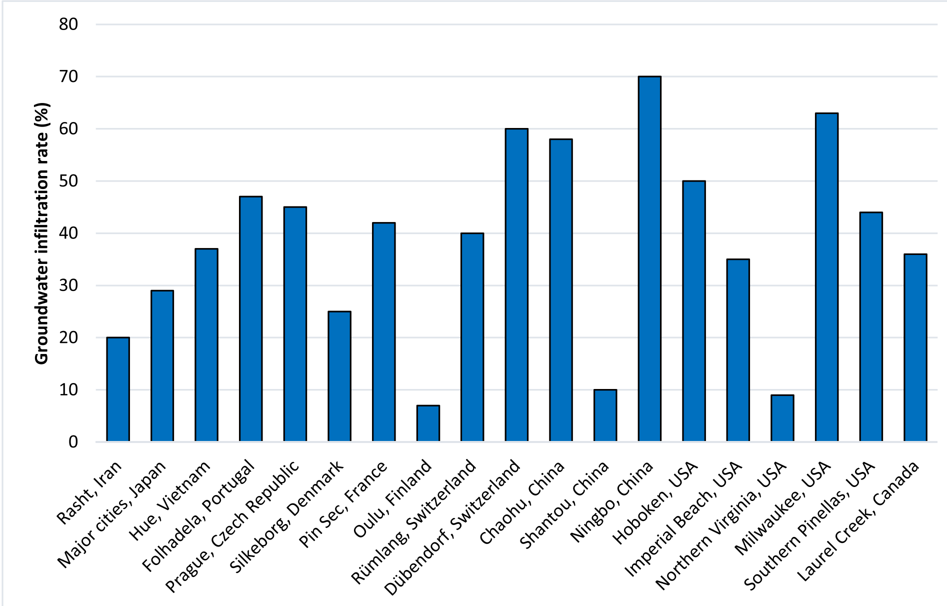

Fig. 7. The ratio of groundwater (due to GWI) in sewer networks in some regions in the world.

associated impacts on streamflow in urban watersheds was discussed by Pangle et al. (2022), who declared that I/I can substantially reduce flows in urban streams, especially low flows during DWCs. While wastewater flows exhibit relatively consistent year-round patterns, the separated GWFs display seasonal fluctuations that may correlate with baseflow in nearby rivers (Wittenberg and Aksoy, 2010).

Even COVID had its own influence on GWI in sewer networks, as water from GWI was calculated to be 7.8 % and 9.4 % of the total sewage flow for COVID and pre-COVID periods, respectively (Perez et al., 2024). This change was attributed to the rise in average daily wastewater resulting from stay-at-home orders.

4.1.4.3. Spatial variations of GWI in sewer networks. Sewer networks and urban streams may interact with the upper portion of the stormwater plume that has infiltrated, causing a local reduction in the water table (Bonneau et al., 2018). Relatively elevated proportion of extraneous water may be primarily associated with the limited total amount of sewage discharge (Yang et al., 2021). GWI into sewer networks is prone to occur in flat regions with a naturally shallow phreatic GWL (Long, 2017), whereas it is expected to be less prevalent in more hilly areas (Dirckx et al., 2016). I/I can vary in different sections of sewer networks based on the origin of extraneous water, such as from snowmelt or storm events (Panasiuk et al., 2019). A relatively minor section of the sewer length could account for the majority of the overall GWI (Zhao et al., 2020).

4.1.4.4. Key factors influencing GWI in sewer networks. Artificial infiltration of surface runoff might potentially increase inflows from infiltration (Weiß et al., 2002). The significance of soil type in determining overland flow must be considered, as it governs the limits of infiltration capacity (Martínez et al., 2021), and its parameters are highly sensitive (Rodriguez et al., 2020). The surface-based direct inflow may be more significantly influenced by the precipitation/evapotranspiration ratio, whereas subsurface infiltration may be primarily controlled by factors like the depth of the water table and the density of defects in the sanitary sewer networks (Zhang and Parolari, 2022).

Infiltration rate and the conductivity of the backfill play a crucial role in computing the leak area (Karpf and Krebs, 2013). Forced infiltration can influence or elevate the local GWL. This increase can lead to significant interactions between the groundwater and the runoff system through drains, overland flow, and the seepage of groundwater into the pipes and canals of the urban runoff network (Kidmose et al., 2015). Stormwater leakage from sewer networks is influenced by the return period of rainfall events, with less GWI during more intense rain events (Peche et al., 2019).

Specific scenarios indicate that population growth and urban development may have a more significant impact on overflows compared to the potential effects of CC (Mahaut and Andrieu, 2019). The varied flow directions at local and regional scales signify the impact of urban configurations on groundwater dynamics (Teimoori et al., 2021). Higher-than-anticipated hydraulic conductivity in a specific domain of model may be attributed to the existence of utilities and infrastructure beneath the urban area, potentially forming preferential pathways for GWF along walls (Su et al., 2022). GWI rate exhibits a negative correlation with imperviousness, pipe length per acre, low intensity, and medium intensity LC/LU (Sebo and McDonald, 2022).

The representation of subsurface infrastructure and near-terrain soil types in models can significantly influence the simulation of high-water levels when the hydrological model is simulated with a finer discretisation. In contrast, when the hydrological model uses a coarser horizontal discretisation, the impact of urban geology on high water levels is less pronounced (LaBianca et al., 2023). Including subsurface infrastructure, despite occupying a small fraction of shallow geology, in the hydrological model alters particle flow paths and travel times to sinks. This leads to less recharge to deeper aquifers and an increased percentage of particles flowing to saturated-zone drains and leaky sewer pipes (LaBianca et al., 2023).

4.1.4.5. Climate change influences on GWI in sewer networks. A surge in GWI with SLR increments due to CC is expected (Fung and Babcock, 2020), such that the approaching decades will likely feature large and increasing percentages of flooded area (Habel et al., 2020). However, SLR-induced groundwater shoaling has much more influence on GWI in sewer networks than solely SLR (Sangsefidi et al., 2023a, b). The growing significance of SLR's effects on GWI in coastal collection systems has been underscored, emphasising the need for their inclusion in facility planning and design (Budd et al., 2020). SLR will have observable effects on increased average DWCs flow, as declared by Budd et al. (2020). Furthermore, daily and seasonal tide ranges can impact normal diurnal flow variations (Budd et al. 2020). Altered GWF dynamics caused by SLR and CC will likely stress aging sewer infrastructure, leading to increased discharge of CSO systems and flooding (Rossi and Toran, 2019). The potential susceptibility of coastal wastewater collection and treatment systems to structural vulnerabilities has been accentuated that may lead to the occurrence of extraneous flows, with GWL being a significant driver of further deterioration of infrastructure and environmental contamination (Cahoon and Hanke, 2019).

4.1.4.6. Effects of sewer conditions on GWI in sewer networks. The density of older housing may serve as a proxy for deteriorating sewage infrastructure, as it may be the most crucial predictor of I/I throughout a specific region (Diem et al., 2022). Aging and faulty sewage infrastructure may act as the primary contributing factors, with particular concern for GWI (Keily, 2019).

Special attention should be given to large diameter pipes, as evidenced by Schulz et al. (2005) research, where 80 % of extraneous water enters the sewer networks through these pipes. Standard-sized defects could lead to GWI into the leaky sewer networks, resulting in a significant drop in local GWL. The condition classes of sewer pipes can be utilised to estimate their potential for infiltration. Furthermore, both groundwater influence and the year of construction were identified as significant indicators for estimating the infiltration potential of sewer pipes (Karpf and Krebs, 2011).

CSOs could even occur during DWCs (Liu et al., 2018). Following sewer repairs, CSOs may decrease or only happen during substantial precipitation (Su et al., 2020). However, it may lead to a rise in GWL, ultimately causing groundwater inundation in the low-lying areas or during high tide in coastal regions (Su et al., 2020).

4.1.4.7. The significance of system monitoring for GWI in sewer networks. A common method to tackle the issue of I/I is to perform short- to medium-term flow monitoring in sewer networks while simultaneously gathering rainfall data to determine the volumes and sources of flows, as stated by Jayasooriya et al. (2015). Sridhar and Parimalarenganayaki (2024) highlighted that addressing sewer leak damages necessitates real-time sewer line monitoring, advanced inspection technologies, and the evaluation of sustainable infrastructure solutions to prevent such incidents. Nguyen et al. (2021) pointed out that water sampling and groundwater monitoring are crucial for calibrating integrated sewer models; however, extensive water monitoring is essential to optimise model parameters (Bareš et al., 2009). Enhanced online monitoring data and superior data quality can reduce uncertainty and improve parameter sensitivity (Zhang et al., 2018b). Fortunately, the ongoing development of innovative sewer network monitoring techniques enhances the understanding of key processes and characteristics of sewer systems, facilitating the creation of mathematical models globally (Nguyen et al., 2021). Sridhar and Parimalarenganayaki (2024) asserted that advanced machine learning approaches can improve real-time monitoring and leak detection accuracy. However, scaling up results from physical experiments and monitoring may lead to overestimation of certain data at larger scales, as underscored by Ellis et al. (2009).

5. Limitations

Modelling GWI in sewer networks is subject to several limitations, including data scarcity, a shortage of case studies, the interdisciplinary nature of such studies, modelling complexities, the intricate nature of GWI processes, urban heterogeneities, scaling constraints, challenges specific to sewer networks, economic factors, and considerations related to decision-makers.

5.1. Shortage of case studies and interdisciplinarity

Groundwater resources have been less emphasised, possibly attributed to an "out of sight, out of mind" perspective (Teimoori et al., 2021). Fewer studies have been undertaken concerning GWI in sewer networks, reflecting an interdisciplinary nature that encompasses various fields such as groundwater, CC, SLR, urban hydrology, and demographic analyses.

Research on GWI in sewer networks may have quantified the ratio of GWI into sewer networks or the source and volume of groundwater in sewer networks (e.g. Zhao et al., 2020; Zhu, 2022). However, reliable figures regarding the actual amount of infiltration as a percentage of the total flow are sparse and are presumed to lack representativeness (Hey et al., 2016). Plus, work on delineating a spatio-temporal risk map of GWI in sewer networks is rarely conducted (Thapa et al., 2019).

Despite existing studies on CC and urban environments, (e.g. the impacts of CC and urbanisation on drainage (Semadeni-Davies et al., 2008), the impacts of CC on urban environment (Pokrývková et al., 2021), the impacts of CC and flooding on sewage networks (Mohammed et al., 2021), and the impacts of CC and rainfall on sewer networks (Gogien et al., 2023)), considering CC along with sewer networks in regard to groundwater has been rarely included in research.

Few studies have conducted at national scales, e.g. Selvakumar et al. (2004). Also, limited studies have explored the influence of human-induced alterations on GWF in the modelling of urban hydrogeology at the city scale (Attard et al., 2017; Berthier et al., 2004); e.g. the impacts of impervious surfaces on groundwater recharge at city scale were studied by Pasquier et al. (2022). Similarly, for the karst aquifers in urban areas limited research has been conducted, which is expected to encompass different difficulties.

The sewer pipeline network is an essential component of urban infrastructure and is significantly susceptible to failure (Ghavami et al., 2020). Hydraulic capacity failure happens when the flow exceeds the pipe's capacity, meaning that the pipe segment is unable to handle wastewater adequately, without any structural or operational issues. This type of failure can be attributed to I/I, wherein groundwater and stormwater infiltrate the sewer networks through connections, manholes, cracks, and defects (Malek Mohammadi et al., 2019). This failure could be analysed to elucidate the resilience of sewer networks concerning GWI, a concept that, as highlighted by Zeydalinejad (2023), has received limited attention in research—referred to as 'groundwater resilience.'

5.2. Data scarcity

Being a part of urban water infrastructure, sewer networks, are subsurface structures, denoting that detailed data on their positions and features are not directly available, often inaccurate, or missing (Mair et al., 2017).

Identifying areas at risk from rising groundwater necessitates taking into account all elements of subsurface water fluxes together with surface water data (Karpf et al., 2007; Sommer et al., 2009). Additionally, it is crucial to have flow data from the sewer networks, especially at the wastewater treatment plant inflow, along with data on rain intensity in the catchment and temperature measurements to differentiate between DWCs and the total discharge (Karpf et al., 2007). However, field surveys inspecting the effect of urbanisation on groundwater dynamics are relatively scarce (Rossi and Toran, 2019). As a result, data on GWI and sewer conditions are usually limited in terms of scope and temporality (Liu et al., 2021).

Models of the urban hydrological system at the city scale frequently face challenges arising from leaking water pipes or sewers, leading to unintended groundwater recharge or drainage. Documentation regarding the location and extent of pipe leakage is often inadequate (Hibbs and Sharp, 2012; Lerner, 2002; Tubau et al., 2017; Vázquez-Suñé et al., 2010; Yang et al., 1999), as are local climatic and hydrological observations (Fletcher et al., 2013; Hutchins et al., 2017; McGrane, 2016; Salvadore et al., 2015).

5.3. Modelling complexities

While simple models may adequately depict the influence of the subsurface on surface hydrology, they might overlook processes and interactions that affect the water cycle and subsurface flow systems in the presence of a shallow GWL (Attard et al., 2016a; Pophillat et al., 2021). Empirical methods have some assumptions which may lead to uncertainties in the GWI estimations; most of them calculate GWI by measuring wastewater discharges in DWCs with no precipitation, or do not consider industrial zones, which produces wastewater (Neshaei et al., 2017). Commercial hydraulic models for sewer networks treat GWI as a constant, determined through low-flow monitoring campaigns, and lack the capability to forecast future flows based on variations in groundwater elevations (Budd et al., 2020). Quick approximations of the occurrence of infiltration water across the entire catchment area, e.g. hydraulic methods used by Kretschmer et al. (2008), can be easily conducted. However, a major drawback of these methods is their inability to pinpoint or narrow down hot spots in the system (Kretschmer et al., 2008). The prevailing sewage estimation methods employed across Australia do not accurately represent actual flow data, at times neglecting significant extraneous flows, relying on generalised values, leading to substantial inaccuracies, and providing misleading sewage flow estimation (Keily, 2019).

Alternatively, thorough numerical groundwater models necessitate precise geological input (LaBianca et al., 2023). Employing every method for computing GWI in sewer networks needs different data, and it has its own steps, assumptions, and uncertainties. In order to simulate GWI in sewer networks using MODFLOW, a specific hydraulic conductance may be utilised for sewer pipes using the Drain package. Groundwater discharge may also be attributed to sewer drains and evapotranspiration (Teimoori et al., 2021). The process differs depending on the employed approach, e.g. a series of modules can represent the urban subsurface realm in shallow groundwater conditions in the urban hydrological model URBS (Pophillat et al., 2021).

Considering urban water budget, GWI may be acquired due to its seasonal characteristics, such that during the dry season rainfall infiltration may be assumed to be zero and sewerage flow would be only the sum of wastewater produced by households and economic activities along with infiltrated water (De Ville et al., 2017). By estimating the premier and measuring the total wastewater flow, the infiltrated water can be approximated. Plus, the least sewage flow occurs before morning (Watanabe et al., 2021).

Regarding the mass spectrometer used by Zhu (2022), the accuracy of the estimation results is greatly affected by uncertainties in water and noble gases sampling and the analysis conducted with the portable device. Furthermore, the presented GWI ratio may be systematically biased due to the strong assumption regarding gas exchange and the associated gas loss factor. Beckley and McHugh (2020) assessed vapor intrusion from groundwater through sewer networks across several sites across the USA using tracer testing, collecting vapor samples from sewer manholes, and groundwater sampling. It was found that areas with an elevated risk of sewer vapor intrusion are those where there is direct interaction between the subsurface source of volatile organic compounds (e.g. groundwater) and the sewer line.

More difficulty occurs with simulations of GWI in sewer networks in urban areas. When examining sewer networks, the modelling becomes even more intricate, e.g. with variations in GWI observed between aging sewer networks (Liu et al., 2021) and those that are relatively new. This usually encompass various processes, such as runoff from paved and impermeable surfaces, flow within the runoff network, overland flow, infiltration through the unsaturated zone, evapotranspiration in green areas, and GWF in the complex urban geological setting (Kidmose et al., 2015).

Urban groundwater models should employ a graded grid size with refinements near sewers and more urbanised regions (Rodriguez et al., 2020). Additionally, enhancing spatially distributed recharge estimations can contribute to the improved performance of the models (Rodriguez et al., 2020).

Frequently, hydrogeological models in urban areas predominantly concentrate on the effects of the subsurface in proximity to a particular construction site (Attard et al., 2016c; Laursen and Linderberg, 2017; Mielby and Sandersen, 2017; Troldborg et al., 2021). Models depicting shallow urban geology necessitate data typically omitted in hydrogeological models, including the positioning of subsurface infrastructure, buildings, and details regarding backfill material. The expanding urbanisation presents challenges in surveying the urban subsurface (Culshaw and Price, 2011; Mielby and Sandersen, 2017; Petrosino et al., 2021), and substantial spatial heterogeneity in the subsurface, coupled with sparse data, introduces significant uncertainty into the modelling (Salvadore et al., 2015).

The necessity of integrated models encompassing surface and subsurface processes at the city scale has been asserted to provide accurate estimations of the impacts of potential changes, contributing to effective urban water resources management (Laursen and Linderberg, 2017; Mielby and Henriksen, 2020). Nevertheless, existing integrated models for urban hydrology frequently simplify the portrayal of subsurface components (Pophillat et al., 2021).

In the realm of modelling, the current challenge involves transitioning from singular evaluations of urban drainage system performance to comprehensive approaches that strive to incorporate as many relevant factors as feasible. These applications not only incorporate the interaction between the sewer networks and surface flow through 1D/2D coupled models but also integrate the rainfall–runoff and infiltration processes for a more thorough system evaluation (Martínez et al., 2021). Common challenges in integrated modelling include insufficient data, poorly described processes, and parameterisation issues, all of which contribute to uncertainties (Fletcher et al., 2013; Pophillat et al., 2021; Salvadore et al., 2015; Schirmer et al., 2013).

Salvadore et al. (2015), Hutchins et al. (2017), and Mielby and Sandersen (2017) propose that a meticulous spatial depiction of LC/LU and geological configurations, at a scale of a few metres, is imperative for urban hydrological modelling. This amplifies the effort required for assembling and processing extensive data compared to conventional hydrogeological modelling, encompassing temporal variations in the urban surface and subsurface (Hutchins et al., 2017; Salvadore et al., 2015).

5.4. Scaling constraints

Scale of the study is one of the factors in the approach being selected for studying GWI in sewer networks. Surface and subsurface processes occur at diverse spatial and temporal scales in a dynamic urban environment (Fletcher et al., 2013; Han et al., 2017; Kidmose et al., 2015; Salvadore et al., 2015; Tubau et al., 2017; Vázquez-Suñé et al., 2016). To address the computational and time-consuming challenges, one suggestion is to explore the reuse of a large-scale regional model as a basis for establishing a more detailed urban hydrological model for a smaller area. Alternatively, in the case of larger urban areas, it could be recommended to adjust the spatial discretisation within the model domain. This adjustment involves implementing a finer discretisation in areas where infrastructure trenches, water facilities, and subsurface constructions are prevalent. Another proposal is to potentially integrate machine learning with an overarching physically based hydrological model, as discussed by LaBianca et al. (2023). Alternatively, upscaling a pilot case study to large-scale research also has its disadvantages. The capacity of infiltration systems at the catchment scale to replenish groundwater recharge and baseflow remains uncertain (Bonneau et al., 2017).

One problem with quantitative analysis of GWI in sewer networks is time steps. Of significance is suitable boundary conditions in groundwater-related infiltration in sewer networks (Kracht et al., 2008). The swift velocities involved in surface runoff and sewer networks processes demand meticulous temporal resolution, a requisite extended to GWF simulations as well (Sommer et al., 2009).

As declared by Sommer et al. (2009), flow velocities are high for surface water and sewer flow, and slower in the groundwater. It may be a challenge to couple these different time steps with each other considering different modelling codes to distinguish the groundwater ratio in the sewer networks. Plus, different time steps have been regarded, e.g. secondly (Martínez et al., 2021), minutely (Rossi and Toran, 2019), hourly (Budd et al., 2020), half-daily (Liu et al., 2018), daily (Su et al., 2020), and even seasonally (Pangle et al., 2022). The modelling codes work with very different time steps (Sommer et al., 2009). Hence, a customised coupling algorithm should be considered (Sommer et al., 2009).

Research covers different time periods of study, from 3 days (Li et al., 2023b) to longer, e.g. 1 year (Rodriguez et al., 2020). Seasonal fluctuations in the behaviour of GWI to sewer networks have been reported. In the case of infiltration, inflow, and exfiltration from Tehran's sewer networks, during winter months least performance was predicted than in the summer months (Rezaee and Tabesh, 2022).

5.5. The intricate nature of GWI processes

The infiltration processes are intricate and exhibit a high degree of heterogeneity throughout the sewer networks, encompassing contributions from both saturated and unsaturated groundwater zones, making the modelling process complex and challenging to verify (Thorndahl et al., 2016). I/I can originate from rainfall, groundwater, surface water or leaking drinking water pipes (Ohlin Saletti, 2021). Wastewater flow is primarily composed of foul sewage, GWI, RDII, and direct surface water intrusion (Guo et al., 2020).

The quantity of I/I exhibits significant variation owing to distinctions in climate, soil composition, urban design, and the condition and design principles of sewer networks. Infiltration trenches have been reported to experience groundwater impact when the unsaturated depth is below 1.5–3 m in sandy loam, 6.5–8 m in silt loam, and 11–12 m in silty clay loam (Locatelli et al., 2015). Some provided figures of I/I may be considered too conservative, possibly influenced by substantial year-to-year variability due to weather changes and a lack of standardised definitions and calculation methods for presenting the data (Hey et al., 2016).

The simultaneous occurrence of a rainfall event and elevated sea levels, leading to an increase in coastal GWL, may give rise to a compound flooding event. Such events have the potential to be more extensive and hazardous compared to individual flooding sources (Sangsefidi et al., 2023a).

Limited knowledge exists regarding the fate of infiltrated water in urban settings, where the use of impervious surfaces like roofs, roads, and pavement obstructs the infiltration of rainfall into the soil, leading to heightened surface runoff and diminished groundwater recharge (Bonneau et al., 2017). Waterlogged regions and wastewater migration routes are essentially controlled by the drainage networks and subsurface structures (Attwa and Zamzam, 2020).

The term 'urban karst,' as introduced by Kaushal and Belt (2012), refers to the interconnected network of constructed pipes (sewers and stormwater systems) that influence GWF. This network includes leaks, cracks, and fissures within the pipes, as well as the high-permeability trenches surrounding them (related to telecommunications and water supply). The concept highlights the creation of preferential flow paths for infiltrated stormwater and associated pollutants, playing a pivotal role in shaping hydrological processes within urban catchments. The pathways through which infiltrated water navigates in the subsurface realm of the urban environment, especially within the context of 'urban karst', as stated by Bonneau et al. (2017), formed by human-made subsurface structures like stormwater and sanitary sewer pipes, along with associated high-permeability trenches, remain unclear (Attard et al., 2016a; Kaushal and Belt, 2012; Vázquez-Suñé et al., 2005). Therefore, simulating urban regions, referred to as 'urban karst,' poses significant challenges, akin to the difficulties encountered in modelling karst aquifers due to their high heterogeneity and anisotropy (Nassery et al., 2021; Zeydalinejad et al., 2020a, b; Zeydalinejad, 2022).

5.6. Urban heterogeneities

The evolution of urban areas over time has had repercussions on shallow groundwater, and forthcoming developments in subsurface environments, including subterranean infrastructure, will impose additional challenges.

In urban areas, the shallow geology undergoes more extensive modifications compared to rural areas, both in terms of its physical extent and the frequency of temporal alterations. This is a direct result of the high population density, leading to the concentration of buildings, physical infrastructure, and extensive networks for transportation and utilities (Attard et al., 2016c; Lerner, 1990, 2002).

The term "anthropogenic layer" is used to describe this shallow geology significantly influenced by human activities (Mielby and Sandersen, 2017; Ford et al., 2014). The anthropogenic layer can exhibit variations in extent and composition within a short distance. Moreover, the composition and characteristics of the anthropogenic layer undergo frequent changes in urban areas due to surface reconstruction, maintenance of existing subsurface installations, or new underground construction (Salvadore et al., 2015; Fletcher et al., 2013; Hibbs and Sharp, 2012; Berthier et al., 2004; Ford et al., 2014). Understanding the city's history is crucial for quantifying the anthropogenic layer, emphasising the need for distinct geological modelling approaches for both the anthropogenic material and the underlying geological sediments (Mielby and Sandersen, 2017). The hydraulic properties of the anthropogenic layer may induce preferential flow pathways (Berthier et al., 2004; Fletcher et al., 2013; Salvadore et al., 2015), while subsurface structures can act as flow obstacles (Hibbs and Sharp, 2012; Lerner, 1990, 2002; Pophillat et al., 2022), leading to enhanced mixing of shallow and deep aquifers (Attard et al., 2016c, 2017).

Considering the dimensions and hydrological characteristics of urban subsurface infrastructure and buildings holds significance, as they impact local GWL, flow paths, sinks, recharge to deeper aquifers, and the residence time of particles in aquifers (LaBianca et al., 2023). Urban areas pose hydrological complexity due to the interplay among constructed structures, water infrastructure (including pumps, drainage, sewers, and water pipes), and the natural hydrological system.

Though it may be considered that because of impervious surface layers in urban areas, groundwater recharge may be lower than natural terrains, Tubau et al. (2017) declared that there are generally higher rates of groundwater recharge in urban settings than in natural settings; hence, all these complexities must be regarded.

6. Future directions

As depicted, numerous facets pertain to groundwater and sewer networks, necessitating the identification of various directions for future perspectives (Table 5).

6.1. Data

Groundwater level is the most critical variable to monitor for various purposes (Zeydalinejad et al., 2023), such as groundwater modelling, as it provides essential data and maps necessary for investigating the GWI process in sewer networks. Advancements in monitoring techniques, digitalisation, and computational power can provide an opportunity to develop intricate integrated hydrological models with diminished uncertainty (Hutchins et al., 2017). The digitalisation of sewer networks data has become a standard practice, and the number of detailed sewer models is steadily increasing (Dirckx et al., 2016). Another consideration is optimisation, with estimates suggesting a potential for up to a 30

Table 5
Proposed adaptation strategies.

Factor	Action
Data	Enhancing field surveys Towards high-resolution data in different subsystems of groundwater infiltration in sewer networks Advancements in monitoring techniques, digitalisation, and computational power
Research	Evaluations on the performance indices of sewer networks regarding groundwater infiltration, e.g. resilience, vulnerability, and sustainability Spatio-temporal groundwater infiltration risk maps for sewer networks Focusing more studies on groundwater infiltration in sewer networks, especially in saturated zone and in different scales Preparing national and even continental manuals Considering different governing factors on sewer networks, e.g. climate change and sea level rise Modelling potential groundwater flooding (or inundation) (or shoaling) considering different future scenarios
Modelling	More numerical and comprehensive approaches Integrating different modelling approaches, e.g. machine learning and physically based ones Integrating groundwater and surface water models Integrating stormwater runoff models with distributed hydrological models GIS, remote sensing, and mapping methodologies along with digital twin technology A combination of groundwater quantity and quality modelling in regard to sewer networks Urban groundwater sustainability, city-scale studies, urban karst
Sewer networks	Installing drainage pipes (a third pipe) alongside existing sewer pipes Replacing septic tanks with a proper sewerage system Considering the ratio of groundwater infiltration in sewer networks in advance Considering separate sewer networks, instead of integrated ones Preventative measures regarding unauthorised connections by establishing clear regulations
Policy	The importance of dialogue between government water and urban-planning departments A shift in our approaches to urban development, consumption, and water management
Socio-economy	consider socioeconomic factors, including race, income, public health, and education level Reconsidering our lifestyle choices Hydrogeoethical assessments Considering specific social, cultural, ecological, and technological contexts
Prioritisation Adaptation	Focusing on more susceptible locations, i.e. the coastal areas Determining and prioritising interventions Interdisciplinary adaptation proposals considering different factors, e.g. CC and SLR Lowering water table through groundwater pumping from shallow wells Afforesting new areas in and around the town Creating a new ditch in the town Towards more concentrated buildings Nature-based strategies (NBS), utilising living organisms, soils, sediments, and landscape features to mitigate climate change hazards

% improvement in accuracy compared to non-optimised gauge distributions.

Additional local-scale observations are essential for a comprehensive understanding of groundwater-sewer interactions and to enhance the accuracy of large-scale modelling endeavours (Rodriguez et al., 2020). This data can be obtained through either (1) physical models that improve estimations of soil parameters to represent the influence area of a sewer trench, or (2) the placement of sensors near sewers (Rodriguez et al., 2020).

Lastly, rather than gathering new data and enhancing field surveys, leveraging existing data would be a prudent initial step (Kretschmer et al., 2008).

6.2. Research

It is advisable to report the GWI ratio for sewer networks as a foundation for comparing various studies. It is vital to prioritise high-risk regions before they trespass the threshold of failure and the cost of repairs increases (Shelton et. al., 2011). Coupling the spatial maps with sewer networks depth will allow establishing network vulnerability maps linked to the groundwater presence and its behaviour (Marache et al., 2006).

Considering different scenarios for future is vital, e.g. (1) considering deterioration and rehabilitation of networks together with their vulnerability, costs, CC, and flooding (Tscheikner-Gratl et al., 2014), and (2) considering integrated wastewater management, e.g. ALLOWS tool (Assessment-of-Local-Lowest-Cost-Wastewater-Solutions) (Breulmann et al., 2022).

Further research is required to elucidate mechanistic explanations for the variability in the influence of I/I on streamflow across urban and suburban watersheds (Pangle et al., 2022).

Multidisciplinary approaches are highly recommended in groundwater-related studies, including GWI quantification in sewer networks, for which not only groundwater science must be understood, but also urban science must be assessed. Indeed, nowadays, we have urban groundwater science, e.g. studies conducted by Arshad and Umar (2020); Bricker et al. (2017); Chaminé et al. (2022); Freitas et al. (2019); Li et al. (2022); Pasquier et al. (2022). Not only groundwater science is influenced by urban environments, but urban infrastructure developments are influenced by groundwater, for which guidelines must be considered (Attard et al., 2017). By urbanisation, urban groundwater science receives more and more importance, considering future city visions, such that instead of groundwater sustainability, urban groundwater sustainability may be proposed, like the studies carried out by Chaminé et al. (2022) and Freitas et al. (2019). Also, urban hydrological models exist, which must be considered for urban groundwater studies (e.g. Li et al., 2022).

Using indices is of significance for judging different systems and subsystems; hence, they are highly recommended such as urban infiltration potential index (IPI-Urban) proposed by Afonso et al. (2020) or severity index and performance index used by Rezaee and Tabesh (2022). Cardoso et al. (2006) also have introduced multiple performance indicators in regard to water infiltration to sewer networks.

In addition to vulnerability to flood events, it is essential to consider socioeconomic factors, including race, income, public health, and education level, when evaluating the overall vulnerability of a community (Bathi and Das, 2016). Different strategies are highly recommended to be tailored to specific social, cultural, ecological, and technological contexts (Hobbie and Grimm, 2020).

Reconsidering our lifestyle choices has been declared (Mahaut and Andrieu, 2019). As inhabitants of Earth and primary stewards of the system consisting of various subsystems, we, as humans, bear the responsibility to uphold hydrogeoethics. It is inherent in our humanity to prevent the degradation of any subsystem, such as the failure to adhere to hydrogeoethics concerning aquifers, as highlighted by Zeydalinejad et al. (2023).

The importance of dialogue between government water and urban-planning departments has been emphasised. Rather than relying solely on technical solutions, addressing the challenges posed by our sewer networks requires a shift in our approaches to urban development, consumption, and water management. Local governments could be prompted to reassess their approaches to urban development, introduce fresh methods for population density, and implement inventive tactics for managing wastewater and rainwater. Strengthened communication between governmental water and urban planning divisions is essential for fostering mutual comprehension of the reciprocal effects of decisions made in each realm. Additionally, there is a suggestion to adjust our behaviours, daily routines, and methods of dwelling within the region (Mahaut and Andrieu, 2019)

6.3. Modelling approaches

Subsequent research should evaluate the model's efficacy across various applications and conduct a more extensive sensitivity analysis encompassing diverse scenarios (Figueroa et al., 2021). Only a handful of studies have endeavoured to integrate a stormwater runoff model with a distributed hydrological model, despite the widespread recognition of infiltration or exfiltration processes between pipes and canals of urban runoff systems and groundwater (Kidmose et al., 2015).

As proposed by Rodriguez et al. (2020), coupling groundwater and surface water models and adopting advanced modelling frameworks, such as the one proposed by Vizintin et al. (2009), can be effective strategies. A combination of groundwater quantity and quality modelling in regard to sewer networks is proposed (e.g. Ly and Chui, 2012). There is substantial room for enhancement in the current standard analytical techniques used in the industry (Zhang, 2005).

Conventional methods may produce comparable results (Bareš et al., 2009). To obtain more precise local information, particularly at the level of sewer pipes, it is necessary to develop urban groundwater models (Dirckx et al., 2016).

Recent advancements in GIS, remote sensing, and mapping methodologies have positioned them as highly valuable tools in various scientific disciplines, particularly in the context of groundwater management, as noted by Afonso et al. (2019). GIS, renowned for its effectiveness in handling both geometric and alphanumeric data, is favoured for tackling multifaceted aspects of environmental modelling. It possesses the capability to store, manage, analyse, and visualise extensive sets of spatiotemporal and even non-spatial data, as emphasised by Kresic and Mikszewski (2012) and Rossetto et al. (2018). Hence, GIS may be used for GWI risk mapping in sewer networks, such as the research conducted by Friedrich and Kretzinger (2012).

Machine learning and AI have been increasingly adopted across various scientific disciplines. However, their application in the context of GWI in sewer networks has been relatively limited, as observed in studies by Liu et al. (2021) and Zhang et al. (2020). This suggests significant potential for their exploration in future studies, given the benefits they offer. The digital twin is currently pivotal in enhancing our understanding of risks associated with past, present, and future climate impacts, as demonstrated by Henriksen et al. (2022) for CC adaptation, water management, and disaster reduction. Its application could extend to risk mapping for GWI in sewer networks.

6.4. Sewer networks

By knowing the GWI into the sewer networks, their capacity can be considered larger than just transmitting sewerage. A common practical design criterion is to consider GWI as 10 to 25 percent (%) of the domestic average DWCs flow (Wittenberg and Aksoy, 2010). Nevertheless, as declared by Bentes et al. (2022), it is essential to consider the magnitude and evolution of different flow rates based on the age and condition of the network, and to establish clear regulations regarding unauthorised connections to the network, as they, in residential areas, likely constitute a major avenue for stormwater entering the sanitary system (Tan et al., 2019).

Replacing septic tanks with a proper sewerage system, as surveyed by Elfeki and Bahrawi (2015), may be considered as a strategy for adaptation towards CC. To address the issue of sewage connections and groundwater seepage into storm drains, end-of-storm pipe interceptor sewers with a capacity of 0.25 m^3/s would be effective (Xu et al., 2014). The effectiveness of sewer rehabilitation in addressing I/I has been examined by Staufer et al. (2012). Using a statistical approach, they concluded 23.9 % reduction in GWI and 35.7 % decline of stormwater inflow in Muetzenich, Germany.

A balance should be always maintained between sewer networks and groundwater. As Thorndahl et al. (2016) stated sealing sewer networks may lead to lower GWI into them, however, that may result in increased GWL, causing problems of groundwater flooding, e.g. groundwater seepage to different infrastructures. Sanitary and storm sewer networks should be designed as separate systems. The inclusion of perforations in storm sewer networks can facilitate partial infiltration of rainfall, serving two purposes: (1) alleviating the load of rainfall runoff and (2) aiding groundwater recharge (Xu et al., 2020).

6.5. Adaptation

Counteracting measures are recommended if the share of infiltration water related to the DWCs exceeds 25 %. Pollution control in existing combined systems could be significantly enhanced by minimising I/I, analogous to the reduction of surface runoff proposed as a frequent alternative (Weiß et al., 2002).

The essential rehabilitation of an existing network must be, to some extent, contributed to adapting to a changing environment (Tscheikner-Gratl et al., 2014). The primary emphasis of adaptation strategies revolves around traditional measures, such as the expansion of sewer networks (Kourtis and Tsihrintzis, 2021), which should change towards more sustainable adaptation strategies, considering CC and SLR, in an interdisciplinary approach, for instance:

(1) Evaluating the effects of short-term extreme precipitation events on sewer networks using hydraulic modelling and proposing mitigation strategies in respect to sanitary sewer overflows in Glenroy, Australia (Nasrin et al., 2017),
(2) Exploring urban flood modelling within sewer networks under CC by employing dependence measures, considering factor and correlation analyses, and machine learning classifier systems in Espoo, Finland (Jato-Espino et al., 2019), and
(3) Employing the hydro-dynamic models, e.g. Storm Water Management Model (SWMM), to simulate excessive rainfall intensities and estimate the maximum water volumes within the combined sewage system based on future events and increasing the diameters of selected pipes within the sewage system in Ahmed Rachdi, Algeria (Ibrahim et al., 2022).

Proposals for addressing the limitations of existing urban sewer networks include the densification of already developed urban areas served by a separative sewer system. This approach avoids the need for road and sewer networks extensions, along with the associated risks of additional GWI into the pipes (Mahaut and Andrieu, 2019).

Making a prioritisation for studies is advisable. For example some regions have more susceptibility to GWI in sewer networks, e.g. coastal areas, for which collection systems are usually below the water table (Fung and Babcock, 2020).

Nature-based strategies (NBS), utilising living organisms, soils, sediments, and landscape features to mitigate CC hazards, offer potential advantages in terms of flexibility, multifunctionality, and adaptability to an uncertain and dynamic climate future compared to conventional methods. However, further research is needed to assess the efficacy of NBS in mitigating CC impacts and their suitability for implementation at scales relevant to climate-related hazards and consequences. The effectiveness and equity of NBS are likely maximised when they align with the scale of the challenge, involving diverse perspectives in their implementation (Hobbie and Grimm, 2020).

7. Summary and conclusion remarks

We have reviewed research on GWI in sewer networks, focusing on quantitative assessments, and observed a limited exploration in this field of study, despite the increasing challenges faced by urban sewer networks, such as population growth, urbanisation, and CC, as asserted by Jia et al. (2021). On the other hand, certain facets of sewer networks, such as wastewater transportation, and the failure of sewer networks, have garnered more attention.

We propose categorising the quantitative examination of GWI in sewer networks into two groups: (1) studies that have considered the phreatic zone, and (2) those that have focused on the vadose zone. Some investigations have explored RDII in sewer networks, which can be interpreted as inflow from surface water and GWI in the vadose zone (group 2). Indeed, research indicates that a comprehensive analysis involving both surface water and groundwater should be considered for the quantitative assessment of GWI into sewer networks, rather than solely focusing on groundwater.

Different approaches have been used in both groups from simple modelling approaches to intricate ones. Numerical modelling, particularly MODFLOW, has been more prevalent regarding the phreatic zone (group 1). Field surveys along with water balance and hydrograph separation approaches have been the predominant methods for the vadose zone (group 2). GIS and AI have received limited attention for both zones.

The choice of a model is crucial in studies related to GWI in sewer networks. In this study, we recommend following the flowchart depicted in Fig. 6 for the steps involved in GWI research on sewer networks. After defining the purpose, collecting data, and analysing the current situation, the model can be selected. Following modelling specific steps, simulations are conducted to ensure the sustainability of groundwater and sewer networks systems.

The trend in studies indicates a growing frequency in the quantitative analysis of GWI into sewer networks, with a more pronounced increase in studies focusing on the groundwater phreatic zone. In recent years, there has been a notable shift towards more comprehensive investigations, encompassing additional factors such as CC, SLR, and interactions between surface water and groundwater. This underscores the importance of their inclusion in the analysis and encourages the consideration of a combination of modelling approaches to characterise the various fluxes, including infiltration, inflow, and exfiltration.

Despite being addressed in a limited number of studies, the consideration of various scenarios involving CC, SLR, temperature changes, and precipitation fluctuations is crucial. These factors significantly heighten the vulnerability of coastal wastewater collection systems – especially, shallow coastal urban groundwater systems –making their evaluation essential. Coastal communities are grappling with the repercussions of SLR induced by CC, with groundwater being notably affected, albeit frequently with insufficient characterisation (Bosserelle et al., 2022).

Based on the conducted studies, various influencing factors have been evaluated in the modelling, e.g. hydrological and sewer networks-related data (Fig. 6). The most crucial input parameters are GWL and the hydraulic conductivity of the surrounding soil. In computing the leak area, factors like conductivity and infiltration rate play a crucial role. Rainfall is also of significance, for which stormwater leakage from pipes may be influenced by the return period of rainfall events, with less GWI during more intense rain events. Different factors may be of more importance for inflow from surface water and infiltration from groundwater, e.g. precipitation/evapotranspiration ratio for the former, and the depth of the water table and the density of defects in the sewer networks for the latter.

The interaction between groundwater systems and sewer networks is evident, as groundwater can influence sewer networks by infiltrating into them. This infiltration can reduce the wastewater conveyance capacity, resulting in issues such as increased treatment loads, CSO spills and potential failure of sewer networks. GWI to sewer networks may occur if water table is above the sewer networks, and vice versa, i.e. aging sewer networks exfiltration above water table may lead to groundwater inundation, as stated by Rossi and Toran (2019). Temporal and spatial factors influence groundwater-related infiltration in sewer networks. For example, elevated GWL during the winter are expected (Rasmussen et al., 2023).

Sewer networks are essential for civilisation. Beyond their advantageous role in curbing environmental issues, e.g. pollution, they possess multifaceted utility. For instance, Figueroa et al. (2021, 2023) underscored their potential in harnessing heat capacities. Sewer networks play a role in safeguarding groundwater from pollution. Without these networks, wastewater could directly infiltrate the ground, resulting in groundwater contamination. Nevertheless, leakage from sewer networks can pose a risk of groundwater pollution at specific points. While their exfiltration may elevate GWL, there have been reports of missing springs and streams in certain locations.

Finally, it should be considered that a myriad of limitations arise when carrying out studies on urban groundwater and sewer networks, e.g. many approaches fail to calculate the actual volume of GWI, potentially including ground infiltration.

CRediT authorship contribution statement

Nejat Zeydalinejad: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Akbar A. Javadi:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **James L. Webber:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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